PDL HANDBOOK SERIES

Handbook of Plastics Joining

A Practical Guide

2nd Edition

Michael Troughton

pdl
Plastics Design Library

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Introduction

The *Handbook of Plastics Joining* is a unique reference publication that provides detailed descriptions of joining processes and an extensive compilation of data on the joining of particular plastic materials. Although the basic characteristics of joining processes are generally well defined by manufacturers, data on joining particular plastics is not well compiled or easily accessed. This volume serves to turn the vast amount of disparate information from wide ranging sources (i.e., conference proceedings, materials suppliers, test laboratories, monographs, and trade and technical journals) into useful engineering knowledge.

Joining a molded plastic part to another part composed of the same or a different plastic material or to a metal is often necessary, when the finished assembly is too large or complex to mold in one piece, when disassembly and reassembly is necessary, for cost reduction, or when different materials must be used within the finished assembly. Thermoplastics are frequently joined by welding processes, in which the part surfaces are melted, allowing polymer chains to interdiffuse. Other methods used in joining plastics are adhesive bonding, in which a separate material applied at the bond line is used to bond the two parts, and mechanical fastening, which uses fasteners such as screws or molded-in interlocking structures for part attachment.

The information provided in this book ranges from a general overview of plastic joining processes to detailed discussions and test results. For users to whom the joining of plastics is a relatively new field, the detailed glossary of terms will prove useful. For those who wish to delve beyond the data presented, source documentation is presented in detail.

As in the first edition, an effort has been made to provide information for as many joining process and material combinations as possible. Therefore, even if detailed results are not available (i.e., the only information available is that a joining process is incompatible for a particular material), information is still provided. The belief is that some limited information serves as a reference point and is better than no information.

Although this publication contains data and information from many disparate sources, in order to make the book most useful to users, the information has been arranged to be easily accessible in a consistent format. Flexibility and ease of use were carefully considered in designing the layout of this book. Although substantial effort has been exerted throughout the editorial process to maintain accuracy and consistency in unit conversion and presentation of information, the possibility of error exists. Often these errors occur due to insufficient or inaccurate information in the source document.

How a material performs in its end-use environment is a critical consideration and the information in this book gives useful guidelines. However, this publication or any other information resource should not serve as a substitute for actual testing in determining the applicability of a particular part or material in a given end-use environment.

This second edition of the *Handbook of Plastics Joining* has retained all the information from the first edition, but it has been revised extensively and updated to include new information generated over the last ten years.

I am indebted to the following polymer joining experts at TWI who were involved in the preparation of this handbook: Chris Brown, Ewen Kellar, Natalie Jordan, Scott Andrews, Ian Jones, Richard Shepherd, Amir Bahrami, Ajay Kapadia, Marcus Warwick, Andy Knight, and Farshad Salamat-Zadeh. Finally, I would like to thank my wife, Sue, and children, Hayley and Bradley, for their patience and understanding throughout the preparation of this book.

How to Use This Book

This book is divided into two major sections. Part 1, comprising Chapters 1–18, provides a detailed description of all the processes available for joining plastics, including some that are still at the development stage. Welding processes that generate heat through friction (spin, vibration, ultrasonic, and friction stir welding), by use of an external heat source (heated tool, infrared, laser, hot gas, extrusion, radio frequency, and flash free welding, and heat sealing) and by heating an implant placed at the joint line (induction, resistive implant, and microwave welding) are described, in addition to solvent welding, adhesive bonding, and mechanical fastening methods.

Part 2 of the book, comprising Chapters 19–43, covers material-specific information. It is an extensive compilation of data on the joining of particular plastics and is organized by materials; trade names, grades, and product forms are also included. Each chapter represents a single generic family (e.g., polyamides) and is then subdivided into individual resin types (e.g., polyamide 6, 66, 11, 12).

The data in Part 2 appear in textual, tabular, image, and graphical forms. Textual information is useful as it is often the only information available, or the only way to provide an expansive discussion of test results. Tables and graphs provide detailed test results in a clear, concise manner. Each table, graph, or figure is designed to stand alone, be easy to interpret, and provide all relevant and available details of test conditions and results.

The book is organized such that the joining processes and the information specific to a material of interest can be found in Part 2; general information about those joining processes can then be found in Part 1. Information of interest can be found quickly using the general index, the detailed table of contents, and through the subheadings within each chapter.

1 Heated Tool Welding

1.1 Process Description

Heated tool welding, also known as hot plate, mirror, platen, butt or butt fusion welding, is a widely used technique for joining injection molded components or extruded profiles.

The process uses a heated metal plate, known as the hot tool, hot plate, or heating platen, to heat and melt the interface surfaces of the thermoplastic parts. Once the interfaces are sufficiently melted or softened, the hot plate is removed and the components are brought together under pressure to form the weld. An axial load is applied to the components during both the heating and the joining/cooling phases of the welding process.

Welding can be performed in either of two ways: welding by pressure or welding by distance. Both processes consist of four phases, shown in the pressure versus time diagram in Fig. 1.1.

In welding by pressure, the parts are brought into contact with the hot tool in Phase I, and a relatively high pressure is used to ensure complete matching of the part and tool surfaces. Heat is transferred from the hot tool to the parts by conduction, resulting in a local temperature increase over time. When the melting temperature of the plastic is reached, molten material begins to flow. This melting removes surface imperfections, warps, and sinks at the joint interface and produces a smooth edge. Some of the molten material is squeezed out from the joint surface due to the applied pressure. In Phase II, the melt pressure is reduced, allowing further heat to soak into the material and the molten layer to thicken; the rate at which the thickness increases is determined by the heat conduction through the molten layer. Thickness increases with heating time—the time that the part is in contact with the hot tool.

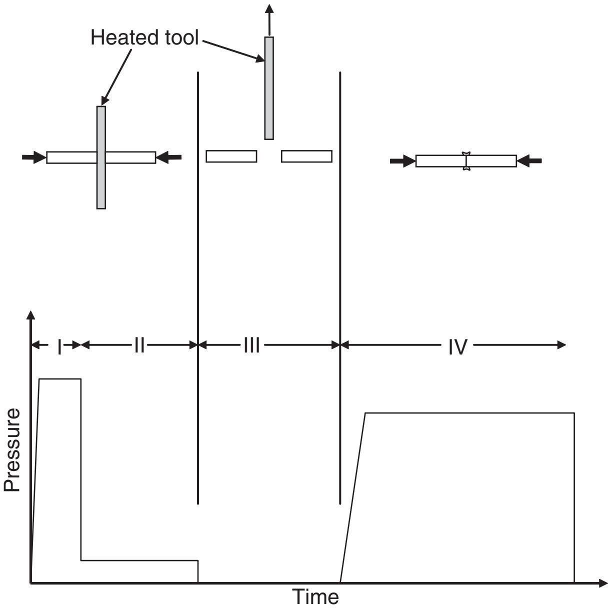


Figure 1.1. Pressure vs. time curve showing the four phases of heated tool welding (Source: TWI Ltd).

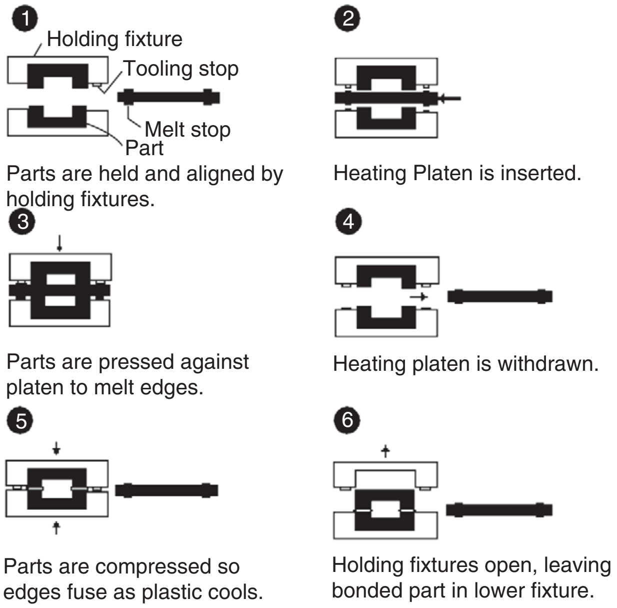
When a sufficient melt thickness has been achieved, the part and hot tool are separated. This is Phase III, the changeover phase, in which the pressure and surface temperature drop as the tool is removed. The duration of this phase should be as short as possible (ideally, less than 3 seconds) to prevent premature cooling of the molten material. A thin, solid "skin" may form on the joint interface if the changeover time is too long, affecting the weld quality.

In Phase IV, the parts are joined under pressure, causing the molten material to flow outward laterally while cooling and solidifying. Intermolecular diffusion during this phase creates polymeric chain entanglements that determine joint strength. Because the final molecular structure and any residual stresses are formed during cooling, it is important to maintain pressure throughout the cooling phase in order to prevent warping. Joint microstructure, which affects the chemical resistance and mechanical properties of the joint, develops during this phase [1, 2].

Welding by pressure requires equipment in which the applied pressure can be accurately controlled. A drawback of this technique is that the final part dimensions cannot be controlled directly; variations in the melt thickness and sensitivity of the melt viscosities of thermoplastics to small temperature changes can result in unacceptable variations in part dimensions.

In welding by distance, also called displacement controlled welding, the process described earlier is modified by using rigid mechanical stops to control the welding process and the part dimensions. Figure 1.2 shows the process steps.

In Step 1, the parts are aligned in holding fixtures; tooling and melt stops are set at specified distances on the holding fixture and hot tool (heating platen), respectively.



Parts are held and aligned by holding fixtures.

Heating Platen is inserted.

Parts are pressed against platen to melt edges.

Heating platen is withdrawn.

Parts are compressed so edges fuse as plastic cools.

Holding fixtures open, leaving bonded part in lower fixture.

Figure 1.2. The heated tool (welding by distance) process (Source: Forward Technology).

The hot tool is inserted between the parts in Step 2, and the parts are pressed against it in Step 3. Phase I, as described for welding by pressure, then takes place. The material melts and flows out of the joint interface, decreasing part length until, in this case, the melt stops meet the tooling stops. Melt thickness then increases (Phase II) until the hot plate is removed in Step 4, the changeover phase (Phase III). The parts are then pressed together in Step 5 (Phase IV), forming a weld as the plastic cools; tooling stops inhibit melt flow. The welded part is then removed in Step 6.

1.2 Advantages and Disadvantages

Heated tool welding is a simple economical technique in which high strength, hermetic welds can be achieved with both large and small parts. Joints with flat, curved, or complex geometries can be welded, and surface irregularities can be smoothed out during the heating phases. Dissimilar materials that are compatible but have different melting temperatures can be welded using hot tools at different temperatures. The welding process can be easily automated with full monitoring of the processing parameters. Since the process does not introduce any foreign materials into the joint, defective welded parts can be easily recycled [1, 3].

The major disadvantage of the process is the long cycle time compared with other common techniques such as vibration or ultrasonic welding. Welding times range from 10–20 seconds for small parts, and up to 30 minutes for large pipes. For the welding of smaller parts, production efficiency can be improved by the use of multiple-cavity tools, allowing simultaneous welding of two or more components.

A second disadvantage is the high temperatures required for melting. Heat is not as localized as in vibration welding, and in some cases can cause plastic degradation or sticking to the hot plate. When the molten surfaces are pressed against each other, weld flash is produced. For certain applications, this must be hidden or removed for cosmetic reasons. In welding by pressure, part dimensions cannot always be controlled reliably due to variations in the molten film thickness and sensitivity of the melt viscosities of thermoplastics to small temperature changes [4].

1.3 Applications

Hot tool welding can be used to join parts as small as a few centimeters to parts as large as 1600 mm (63 inches) in diameter, such plastics pipes (Section 1.9.2). It can also be used for the continuous welding of lining membranes (Section 1.9.3).

The heated tool welding method is widely used in the automotive sector, where one of the most common applications is the welding of vehicle tail lights and indicators (Fig. 1.3). The housing, usually made of acrylonitrile-butadiene-styrene (ABS) is welded to the colored lens which is made from either polymethylmethacrylate (PMMA) or polycarbonate (PC). These represent one of the few material combinations that are compatible for heated tool welding. ABS to PMMA

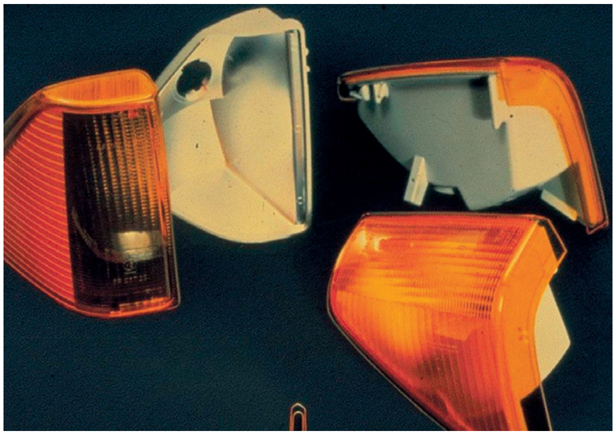


Figure 1.3. Hot plate welded vehicle indicator lamps (Source: Branson Ultrasonics Corp.).

lights can be welded using a single hot plate, because their melting points are similar. Dual hot plates are necessary for ABS to PC. Vacuum fixtures with suction cups are employed to limit any scuffing to the lens.

Custom-built heated tool welding machines are used in the manufacture of blow-molded high density polyethylene (HDPE) fuel tanks. These can require as many as 34 parts to be welded onto the tank, such as clips, filler necks, vent lines, and brackets.

Other automotive components welded by heated tool include battery casings, carburetor floats, coolant and screen wash reservoirs, and ventilation ducts.

Domestic appliance components welded by heated tool include dish washer spray-arms, soap powder boxes (Fig. 1.4), and steam iron reservoirs.

Miscellaneous items welded by the process include lids on HDPE barrels, sharps boxes for medical needle disposal, polypropylene (PP) transport pallets, and the corners of polyvinyl chloride (PVC) window frames.

1.4 Materials

Heated tool welding is suitable for almost any thermoplastic, but is most often used for softer, semicrystalline thermoplastics such as PP and PE. It is usually not suitable for nylon or high molecular weight materials. The temperature of the molten film can be controlled by regulating the hot tool temperature so that plastics that undergo degradation at temperatures only slightly above the melting temperature can be welded.

The properties of the plastics to be welded affect the strength of the weld, including melt viscosity and density. Lower melt index polymers produce higher melt viscosities and can tolerate higher heating temperatures without melt sticking to the hot tool. As a result, the size of the heat affected zone (HAZ)—the area of the part affected by heat—can be larger, resulting in a higher strength joint. For a constant melt index, increasing polymer density results in joints with lower tensile strength. Higher density polymers have a greater proportion of crystalline regions, which melt in a narrower temperature range than polymers of lower crystallinity. As a result, a thinner HAZ and more brittle welds are obtained [5].

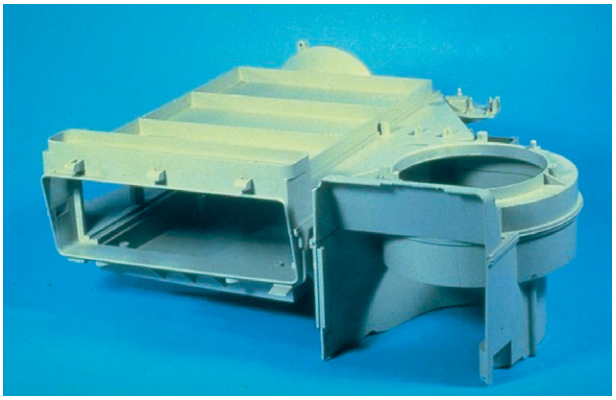


Figure 1.4. Hot plate welded soap powder housing (Source: Branson Ultrasonics Corp.).

In hygroscopic materials such as PC and nylon, absorbed water may boil during welding, trapping steam and lowering the weld strength. High weld strengths can be obtained by pre-drying materials; alternatively, processing parameters can be adjusted to compensate for absorbed water [6].

Dissimilar materials having different melting temperatures can be welded by heated tool welding, provided they are chemically compatible; instead of a single plate with two exposed surfaces, two plates are used, each heated to the melting temperature of the part to be welded. Different melt and tooling displacements and different heating times for each part may be necessary, and due to different melt temperatures and viscosities, the displacement of each part will be different. High strength welds equal to the strength of the weaker material can be achieved [4].

1.5 Weld Microstructure

Weld quality is determined by the microstructure of the HAZ of the weld. The HAZ consists of three zones in addition to the weld flash. The stressless recrystallization zone consists of crystals with a spherulitic shape, indicating that crystallization occurred under no significant stress. This zone results primarily from reheating and recrystallization of the skin layer and the molten layer near the joint interface. The columnar zone consists of elongated crystals oriented in the flow direction; lower temperatures in this zone lead to an increase in melt viscosity, and crystals formed during melt flow aligned with the flow direction. In the slightly deformed zone, deformed spherulites are present, resulting from recrystallization under the joining pressure. Higher heating temperatures result in larger HAZs and greater bond strength; however, too high a temperature or pressure results in void formation at the joint interface [1].

1.6 Equipment

Depending on the components to be welded, heated tool welding machines can be standard models or specialized, custom units. Standard machines have the capability of welding different components by means of interchangeable hot plates and tooling fixtures. These tend to be more labor-intensive, requiring manual loading and unloading of the components. Custom machines are usually dedicated to one particular component and may form part of a high volume, integrated production line. These will often feature a high degree of automation including conveyor feeding and component removal devices, typically with robotic assistance.

The key components of a heated tool welding machine are the hot plate assembly with two exposed surfaces, fixtures for holding the parts to be welded, and the actuation system for bringing the parts in contact with the hot plate and forming the weld. Dual platen hot tool welding machines are used for welding dissimilar materials.

Hot plates are usually made from aluminum alloys, which are good conductors of heat and are corrosion resistant. For complex joints, contoured plates are used that match the profile of the joining surfaces. A number of electrical heating cartridges are positioned within the structure of the plate, to ensure even temperature distribution across both faces. A thermocouple, positioned close to the plate surface, regulates the temperature, typically within 10°C (18°F) of the set point. A coating of polytetrafluoroethylene (PTFE), bonded to the plate surfaces, prevents sticking of the molten polymer during the changeover phase. Since PTFE starts to degrade at 270°C (518°F), the temperature of the hot plate should not exceed this value. For high temperature welding (Section 1.9.1), an aluminum-bronze hot plate without PTFE coating is used.

For accurate mating and alignment, holding fixtures (collets, gripping fingers, mechanical devices, and vacuum cups) must support the parts to be joined, to avoid deformation under welding pressures. Pneumatic or hydraulically activated mechanical fixtures are preferred. Complex shapes or those with delicate surfaces may employ vacuum suction cups. To increase productivity, two or more tool cavities are used for holding the parts.

The actuation system is powered by either pneumatics or hydraulics to give accurate alignment and pressure control. The response must be rapid to ensure that the molten faces break away cleanly from the hot plate surface at the end of heating, and to ensure that the changeover phase is as short as possible.

Statistical control of weld cycles can be achieved through operator control panels that display all machine parameters and diagnostic functions, and pressure or displacement can be programmed throughout the welding cycle. Part conveyors or drawer-load features are optional equipment. A typical heated tool welding machine is shown in Fig. 1.5.

Figure 1.5. A typical semiautomatic heated tool welding machine (Source: Branson Ultrasonics Corp.).

1.7 Joint Design

The choice of joint design depends on the application for the welded part. The squeeze flow in heated tool welding always produces weld flash, which for some applications can be objectionable. Flash traps can be incorporated into the design to hide the flash (Fig. 1.6).

Load transfer through the weld can be increased by enlarging the joint surfaces, as shown in Fig. 1.6b. This is desirable when welding plastics with a high filler

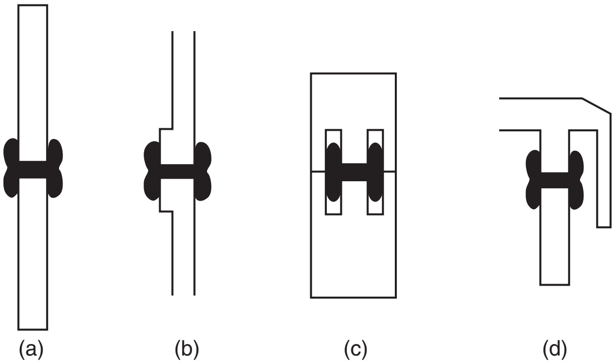


Figure 1.6. Joint designs for heated tool welding: (a) simple butt joint; (b) increased joint area; (c) double flash trap; (d) skirt joint (Source: TWI Ltd).

content, as there is less weldable material available at the joint line. Figure 1.6c shows a double flash trap joint, which entirely conceals the weld flash. It should be noted that the load carrying capacity is significantly reduced, as the welded area accounts for less than 50% of the wall section. Figure 1.6d shows a skirt joint, which would be used when welding lids onto containers. Automotive batteries are a typical example.

1.8 Welding Parameters

Important processing parameters for heated tool welding are the hot plate temperature, the pressure during Phase I (matching or heating pressure), heating time, displacement allowed during heating (heating displacement), melt pressure during Phase II, changeover (dwell) time, pressure during Phase IV (weld, joining, or consolidation pressure), duration of Phase IV (consolidation time or welding time), and displacement allowed during Phase IV (welding displacement).

The hot plate temperature is set in accordance with the melting point of the material to be welded. It is usually in the range 30°C–100°C (54°F–180°F) above the melting point of the thermoplastic. An exception is high temperature welding (Section 1.9.1), which uses a plate temperature between 300°C (572°F) and 400°C (752°F).

The Phase I (matching) pressure is typically in the range 0.2–0.5 MPa (29–72.5 psi) and ensures that the parts conform to the geometry of the hot plate. Moldings often display some degree of warpage, so this pressure ensures that the whole joining interface contacts the hot plate surface for good heat transfer. The pressure must not, however, cause the parts themselves to deform.

The heating pressure (Phase II) is lower than the Phase I pressure and maintains the parts in contact with the hot plate. If this pressure is too large, an excessive amount of molten material will be squeezed out of the joint line.

The joining pressure (Phase IV) brings the two molten faces together and is controlled so that the right amount of material remains at the joint line. If too much material is squeezed out, there is the risk of a "cold weld" forming (i.e., all the hot material is forced out from the HAZ), leaving only cooler material to form the weld. On the other hand, if the pressure is too low, there is the possibility of entrapped air at the joint line or the surfaces not making intimate contact. This will limit molecular diffusion across the joint line and result in a weak weld.

In welding by distance, the parameters should be set so that the displacement (also called the penetration)—the decrease in part length caused by the outflow of molten material—is large enough to control part dimensions. Initially in the welding process, there is very little molten flow, and the molten film thickens. The flow rate increases with heating time, eventually reaching a steady state at which the rate of outflow equals the rate at which the material is melting; at this point in welding by pressure, the penetration increases linearly with time. When displacement stops are used, however, the penetration ceases when the melt displacement stops come into contact with the hot tool displacement stops. Until the stops come into contact, the melt will flow out laterally; afterward, the thickness of the molten material increases with time.

Molten layer thickness is an important determinant of weld strength. If the thickness of the molten layer is less than the melt stop displacement, melt stops cannot contact holding stops, part dimensions cannot be controlled, and joint quality is poor due to limited intermolecular diffusion. In addition to contributing to weld strength, adequate displacement in Phases I and II compensates for part surface irregularities and ensures that contaminated surface layers flow out before the joining phase [7].

Melt thickness increases with heating time. For optimal molten layer thickness, the heating time should be long enough to ensure that the melt thickness is as large as the melt stop displacement. High heating pressures result in larger amounts of squeeze flow; displacement stops may not be reached if too much material is lost by being squeezed out of the joint, and the decreased molten layer thickness produces a brittle weld. If the molten layer thickness is greater than the melt stop displacement, molten material will be squeezed out, producing weld flash and an unfavorable molecular orientation at the interface; this also reduces the quality of the joint [7–9].

Quality control in production can be implemented by monitoring parameters during the welding process; if one parameter is not within a specified tolerance range, the welding machine either produces a signal or stops the welding process. More sophisticated techniques include statistical process control (SPC), in which parameters and melt characteristics are monitored and compared throughout the welding cycle, and continuous process control (CPC), in which optimum parameters are continuously calculated, with the welding machine adjusting conditions as necessary throughout the welding process [10].

1.9 Variants of Heated Tool Welding

1.9.1 High Temperature Welding

During heated tool welding of some thermoplastics, especially those whose melt strength and viscosity are low, sticking to the hot plate and stringing of the melt can be a problem. The melt that remains on the hot plate can then degrade and transfer to subsequent welds, resulting in welds of poor mechanical and visual quality. To avoid this, high temperature heated tool welding can be used, where the hot plate surface temperature ranges between 300°C (572°F) and 400°C (752°F), depending on the type of plastic welded. Since the PTFE nonstick coating starts to degrade at temperatures above 270°C (518°F), the heated plates are not coated.

The process sequence is identical to conventional heated tool welding, except that the times for Phases I and II are extremely short—typically 2–5 seconds. At such high temperatures, the viscosity of the melt is much lower and the melt tends to peel off the hot plate in a cleaner manner when the parts are removed. Any residual material that remains on the hot plate surface then evaporates or oxidizes, resulting in a clean hot plate for the next welding cycle. For this reason, fume extraction devices should be installed above the welding machine to remove the vaporized material.

Due to the high temperatures, thermal degradation of the surfaces to be welded can also be expected. However, any degraded material will tend to be forced out into the weld beads during Phase IV and the weld quality will be affected only slightly, although reduced weld strengths have to be expected with this process.

High temperature heated tool welding has been shown to produce good results for PP and PP copolymers (e.g., for welding automotive batteries) and for ABS and acrylic (e.g., for welding automotive rear light clusters). For reinforced or filled plastics, residues on the hot plate do not evaporate or oxidize completely, so devices are required that automatically clean the hot plate between welds.

1.9.2 Heated Tool Welding of Plastics Pipes

The joining of plastic pipes is one of the most common applications of heated tool welding. The processes of butt fusion, socket fusion, and saddle/sidewall fusion are described below.

1.9.2.1 Butt Fusion

Hot plate welding is a widely used technique for welding pipes made from PE, PP, and polyvinylidene fluoride (PVDF), where it is commonly called butt fusion welding, and the process principles are identical to conventional heated tool welding.

Butt fusion welding machines can be either manual, semiautomatic, or automatic in their operation. With a manual machine, all the welding times and pressures are set and controlled by the operator. In a semiautomatic welding machine, the times and pressures are set and controlled by an electronic user interface, while the trimmer and heater plate are manually controlled. With a fully automatic machine all the welding parameters are set and controlled by a microprocessor, with hydraulic actuation of the trimmer and heater plate. Typical butt fusion welding machines are shown in Figs. 1.7–1.10.

All types of butt fusion machines consist of the following essential components: heater plate, planing device, pipe clamp support carriage, various-sized pipe clamps, and a control unit (manual or microprocessor).

The electrically powered heater plate, typically made from aluminum, is used to uniformly heat the pipe ends. It should have a suitable controller to regulate the temperature within a given range for the material being welded. The surface of the plate is usually coated with a nonstick PTFE coating to prevent a buildup of residual material, which could lead to weld contamination. In some equipment, the PTFE coating is on a separate faceplate that can be changed if the surface coating becomes damaged. A clean, thermally insulated protective holder that shields the plate from contact with the ground and against dust and draughts is usually provided for the plate when not in use.

The planing tool, sometimes called the trimmer, shaving tool, or facing tool, is used to accurately trim the pipe ends so that they are parallel prior to heating.

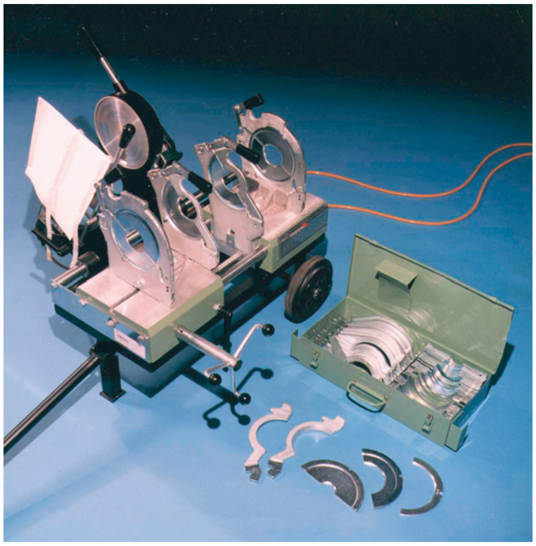


Figure 1.7. Manual butt fusion welding equipment (Source: TWI Ltd).

Figure 1.8. Semiautomatic butt fusion equipment, showing (clockwise, from top left): heater plate (within protective holder), trimmer, hydraulic control unit, data printer, and welding machine carriage (Source: TWI Ltd).

Figure 1.9. Semiautomatic, all-terrain butt fusion welding machine (Source: TWI Ltd).

Figure 1.10. Workshop butt fusion welding machine for large diameter pipes (Source: Plasflow Ltd).

The clamp support carriage, held within the frame, is the main part of the equipment for clamping and supporting the pipes during welding. This part of the butt fusion welding machine is designed around the largest pipe diameter it is required to weld. Reducing clamps or "shells" are inserted in order to clamp pipes that are smaller in diameter. The clamps surround the circumference of each pipe, usually at two positions. The clamp shells often contain serrations or have a grit blast finish to improve the grip on the pipe surface. In some equipment, narrow clamps can be used to hold pipe stubs, flanges, and bends, which do not have sufficient length to be gripped by standard, thicker clamps. The clamp support carriage has two guide elements, typically parallel steel bars, on which the clamps can move back and forth, powered by the rams.

The control unit is used to power the rams for opening and closing the carriage and for providing adequate force during welding. In manual machines this is a simple hand-operated spring mechanism that can be locked off at the appropriate force, indicated on a linear scale. Semiautomatic and fully automatic machines have an electro/hydraulic power pack. A user interface allows setting of the pressures and times (usually by selecting the pipe size and wall thickness), and a pressure gauge is provided to monitor ram pressure values during the fusion cycle.

On manual machines, a data plate is attached to the unit detailing weld pressure and times for specified sizes of pipe. Automatic machines will have the weld parameters programmed into their microprocessor control system.

Many microprocessor-based control units have a data recording facility, which records and stores all welding parameters. These can be downloaded later and serve as a useful quality assurance record.

The key parameters for butt fusion welding of pipes are temperature, heating time, welding pressure, and cooling time. Hot plate temperatures between 200°C (392°F) and 250°C (482°F) are used for PE, PP, and PVDF materials. Heating and cooling times are based on the wall thickness of the pipe to be welded, increasing with increasing wall thickness. Welding pressures are in the range 0.1–0.5 MPa (14.5–72.5 psi) depending on the material and standard used. There are many national and international standards in existence that govern the parameters and procedures for butt fusion welding of pipes. Draft International Standard ISO/DIS 21307 has been prepared in an attempt to harmonize the many standards for welding of PE pipe materials up to 70 mm (2.76 inches) in wall thickness [11].

A feature of all butt fusion welds is the weld "flash" or "bead" created at the joint line as molten material is squeezed out (Fig. 1.11). Examination of the bead can give qualitative information about the weld. For example, if the bead is too small or too large, it can indicate deficiencies in the welding parameters (i.e., pressure, heating time, or temperature being too low or too high, respectively). Removal of the weld bead is a standard practice in some sectors and countries as a quality assurance check. By twisting and bending the bead, contamination defects can be detected, revealed by splitting along the center line of the bead.

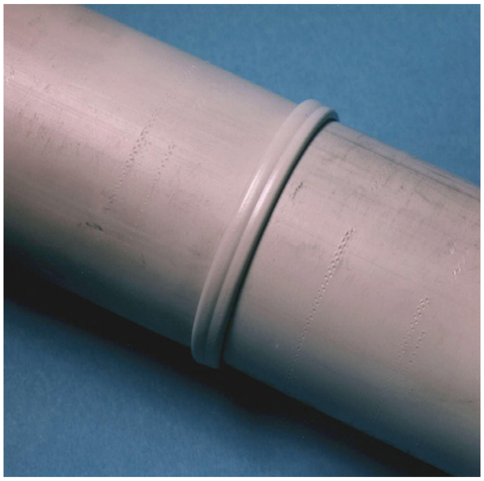


Figure 1.11. Completed butt fusion weld (Source: TWI Ltd).

1.9.2.2 Socket Fusion

The socket fusion technique is mainly used for welding pipes up to 125 mm (4.92 inches) outside diameter (OD) made from PE, PP, and PVDF. The process involves the use of an injection-molded socket fitting. Male and female heating tools, attached to a hot plate, are used to simultaneously heat the inner surface of the socket and the outer surface of the pipe (Fig. 1.12). After a set period of heating time, the heated pipe and fitting are removed from the tools and the pipe end is pushed inside the fitting, producing a weld.

Socket fusion welding can be performed using simple hand tools or with a manual butt fusion machine with modified hot plate and tools. For socket fusion welding by hand (Fig. 1.13), a simple electrically powered hot plate is used, onto which the socket and spigot tools are attached. Normally a table support, floor support, or a fixing clamp is provided.

For pipe sizes over 50 mm (1.97 inches) OD, the socket fusion process can be carried out on a manual butt fusion welding machine. The normal heater plate is removed and replaced by one with a central fixing hole, which allows attachment of the socket and spigot tools to either side of the plate. It is important that the contact faces are clean and flat, to allow maximum heat transfer. Not all designs of manual butt fusion welding equipment will be suitable for socket fusion welding. Due to the shape and size of the injection-molded fittings, the pipe clamps generally

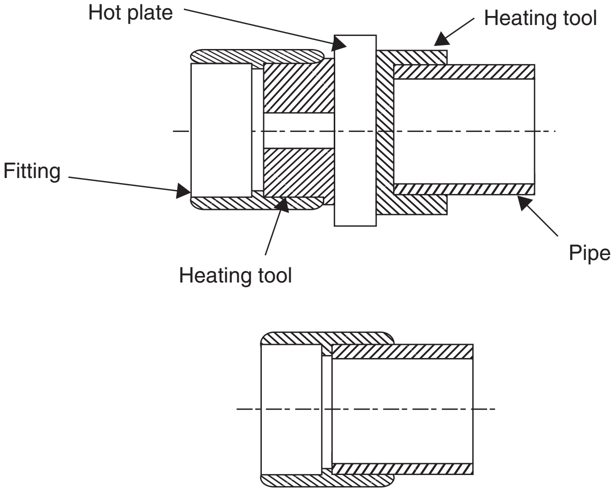


Figure 1.12. Schematic of socket fusion welding process (Source: TWI Ltd).

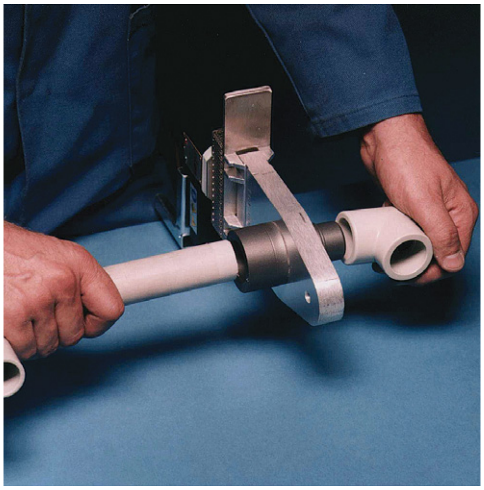


Figure 1.13. Manual socket fusion welding (Source: TWI Ltd).

need to be narrow compared with equipment that is designed solely for butt fusion welding.

The heating socket and spigot tools are typically made from aluminum and coated with a PTFE nonstick surface. This prevents the molten plastic from sticking to the heating surfaces during welding. The dimensions of the socket and spigot are critical for achieving effective heating.

The key parameters of socket fusion welding are temperature, heating time, and cooling time. Pressure is governed by the interference fit between the pipe and socket fitting, so it is vital that these are within tolerance limits along with the heating tools. Typically, welding temperatures between 250°C (482°F) and 270°C (518°F) are specified. A completed socket fusion weld will have two circumferential beads where the pipe enters the fitting (Fig. 1.14). Any problems with equipment set-up or welding parameters will be revealed by the visual appearance of the weld bead.

1.9.2.3 Saddle/Sidewall Fusion

This technique is used to join saddle type fittings onto main pipes to create branch connections. Using convex and concave heating tools, the outer surface of the pipe and the matching surface of the saddle are simultaneously heated for a set time (Fig. 1.15). After this heating period, the heating tools are removed and the two surfaces are brought together with controlled force [12].

A typical saddle fusion machine consists of a holding device to grip the fitting, an applicator assembly with a force gauge, a heating tool with convex and concave heads, and a support system to clamp the whole device to the main pipe, on either side of the intended fusion area (Fig. 1.16). The design allows fusion force to be applied through the centerline of the pipe.

Figure 1.14. Completed socket fusion weld (Source: TWI Ltd).

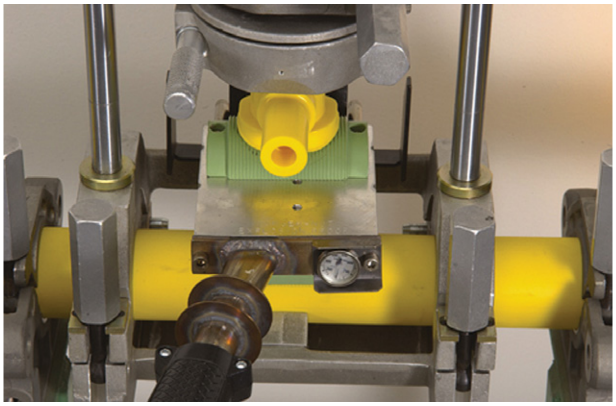


Figure 1.15. Simultaneous heating of pipe surface and saddle base (Source: McElroy Manufacturing Inc.).

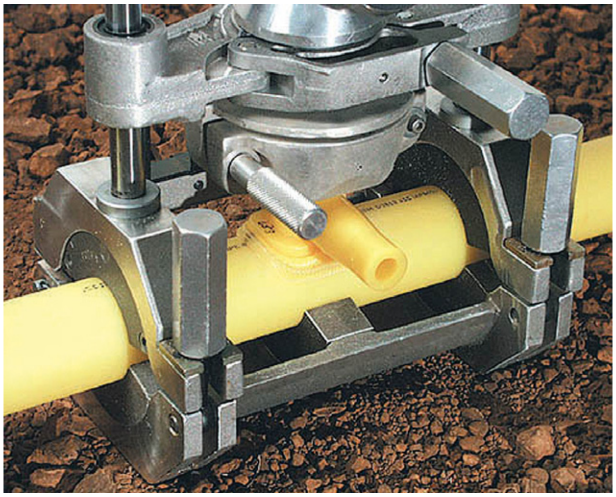


Figure 1.16. Completed saddle weld (Source: McElroy Manufacturing Inc.).

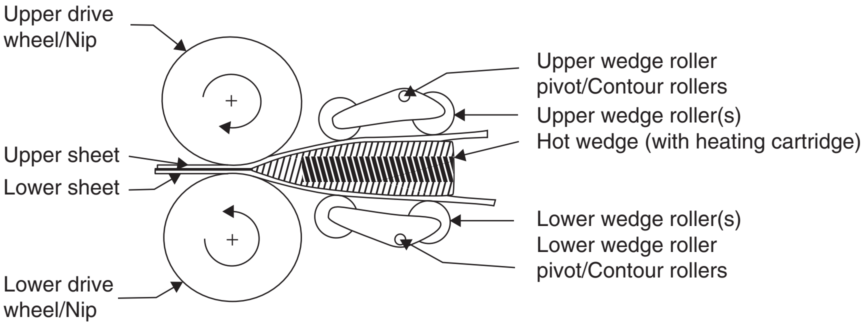


Figure 1.17. Side elevation of a heated wedge welder in a seam (Source: British Geomembrane Association).

1.9.3 Heated Wedge Welding

Heated wedge welding is a specialized type of heated tool welding, which is also known as hot wedge or hot shoe welding. It is used for joining thin sheet materials or membranes together in an overlap joint configuration.

The heated wedge method consists of an electrically heated resistance element in the shape of a wedge that travels between the two sheets to be seamed. The sheets are forced into intimate contact with the hot surface of the heated wedge by means of the wedge rollers, which apply pressure. As it melts the surfaces of the sheets being seamed, a shear flow occurs across the upper and lower surfaces of the wedge. Roller pressure is applied as the two sheets converge at the tip of the wedge to form the final seam (Fig. 1.17). Heated wedge units are automated for temperature, amount of pressure applied, and speed of travel. An example of a heated wedge welding machine is shown in Fig. 1.18.

Two types of joint can be produced using heated wedge welding: single seam (single track) and dual seam (double track). The dual seam (Fig. 1.19) has the advantage that it generates an unwelded channel that can be pressurized with air after the completion of the weld in order to nondestructively test the integrity of the joint.

The geometry of the wedge used to produce a dual seam is shown in Fig. 1.20.

The three important parameters in heated wedge welding are temperature, pressure, and speed. With the welding of geomembranes and other linings outdoors, the setting of the parameters will depend greatly on the ambient temperature on any given day. If the ambient temperature is low, the liner/membrane is more rigid, which means that the welding speed has to be low to ensure that the proper relationship between temperature, pressure, and speed of the welding machine is maintained. As the ambient temperature rises, it will have the effect of softening the material, requiring the speed to be increased in order to avoid overheating of the welded seam. Welding in windy conditions can also be problematic, due to the cooling effect this has on the wedge, in addition to possible air-borne contamination entering the weld.

The typical temperature range for wedge welding of HDPE membranes is 220°C–400°C(428°F–752°F). Wedge welders are self-propelled and the speed is

Figure 1.18. Heated wedge welder in action (Source: TWI Ltd).

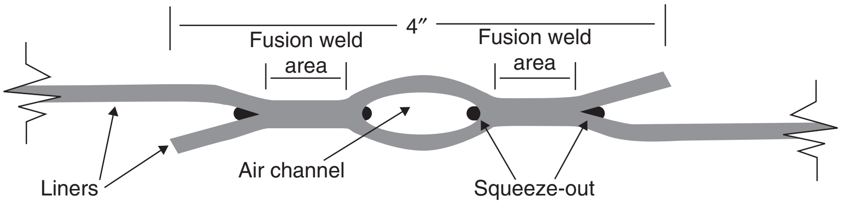


Figure 1.19. Double track fusion weld (Source: British Geomembrane Association).

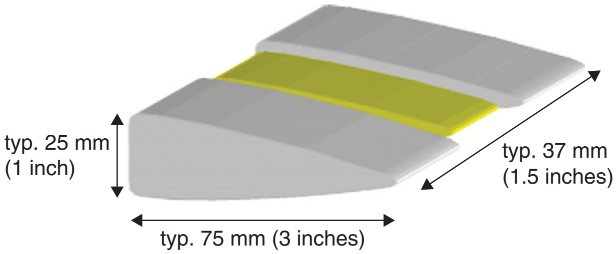


Figure 1.20. Dual (split) heated wedge (Source: British Geomembrane Association).

typically in the range 0.7–4 meters per minute (2.3–13.1 feet per minute), depending on the membrane thickness and ambient conditions; the thicker the sheet, the slower the welding speed.

The pressure necessary to produce a good weld is provided by adjusting the drive rollers. The setting will vary depending on the thickness of the material to be welded. The drive rollers feature embossed/knurled surfaces to assist with gripping. A visual inspection of the impression created by the rollers on the liner surface can assist in adjusting the pressure. Heavy or deep markings indicate too much pressure.

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2 Ultrasonic Welding

2.1 Process Description

Ultrasonic welding, one of the most widely used welding methods for joining thermoplastics, uses ultrasonic energy at high frequencies (20–40 kHz) to produce low amplitude (1–25 μm) mechanical vibrations. The vibrations generate heat at the joint interface of the parts being welded, resulting in melting of the thermoplastic materials and weld formation after cooling. Ultrasonic welding is the fastest known welding technique, with weld times typically between 0.1 and 1.0 seconds.

In addition to welding, ultrasonic energy is commonly used for processes such as inserting metal parts into plastic or reforming thermoplastic parts to mechanically fasten components made from dissimilar materials.

When a thermoplastic material is subjected to ultrasonic vibrations, sinusoidal standing waves are generated in the material. Part of this energy is dissipated through intermolecular friction, resulting in a build-up of heat in the bulk material, and part is transmitted to the joint interface where boundary friction causes local heating. Optimal transmission of ultrasonic energy to the joint and subsequent melting behavior is therefore dependent on the geometry of the part, and also on the ultrasonic absorption characteristics of the material.

The closer the source of the vibrations is to the joint, lesser the energy that is lost through absorption. When the distance from the source to the joint is less than 6.4 mm (0.25 inches) the process is referred to as near-field welding. This is used for crystalline and low stiffness materials, which have high energy absorption characteristics. When the distance from the source to the joint is greater than 6.4 mm (0.25 inches), the process is referred to as far-field welding. This is used for amorphous and high stiffness materials, which have a low absorption of the ultrasonic energy.

Heat generated is normally highest at the joint surface due to surface asperities, which are subjected to greater strain and frictional force than the bulk material [1–3].

For many ultrasonic welding applications, a triangular-shaped protrusion, known as an energy director, is molded into the upper part. This is used to concentrate ultrasonic energy at the joint interface (Fig. 2.1).

During welding, vibration is perpendicular to the joint surface, and the point of the energy director is forced into contact with one of the parts being welded. Heat generation is greatest at this point, and the energy director melts and flows into the joint during Phase 1 of the welding process (Fig. 2.2). The displacement—the decrease in distance between the parts that occurs as a result of melt flow—increases rapidly, then slows down as the molten energy director spreads out and contacts the lower part surface, and the melting rate then drops. In Phase 2, the part surfaces meet, and the melting rate increases. Steady-state melting occurs in Phase 3; a constant melt layer thickness forms in the weld, accompanied by a constant temperature distribution. After a specific time has elapsed, or after a particular energy, power level, or distance has been reached, the power is turned off, and ultrasonic vibrations cease at the start of Phase 4. Pressure is maintained, causing some additional melt to be squeezed out of the joint interface; a molecular bond is created and the weld then cools [2–4].

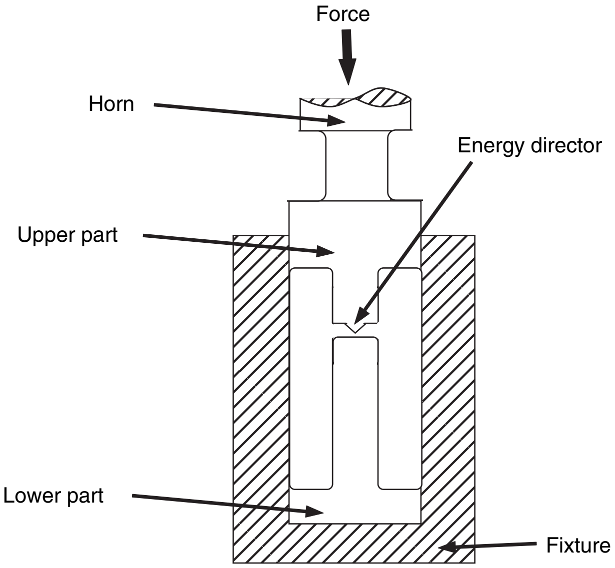


Figure 2.1. Ultrasonic welding using an energy director (Source: TWI Ltd).

2.2 Advantages and Disadvantages

Ultrasonic welding is one of the most popular welding techniques used in industry. It is fast, economical, easily automated, and well-suited for mass production, with production rates up to 60 parts per minute being possible. It produces consistent, high-strength joints

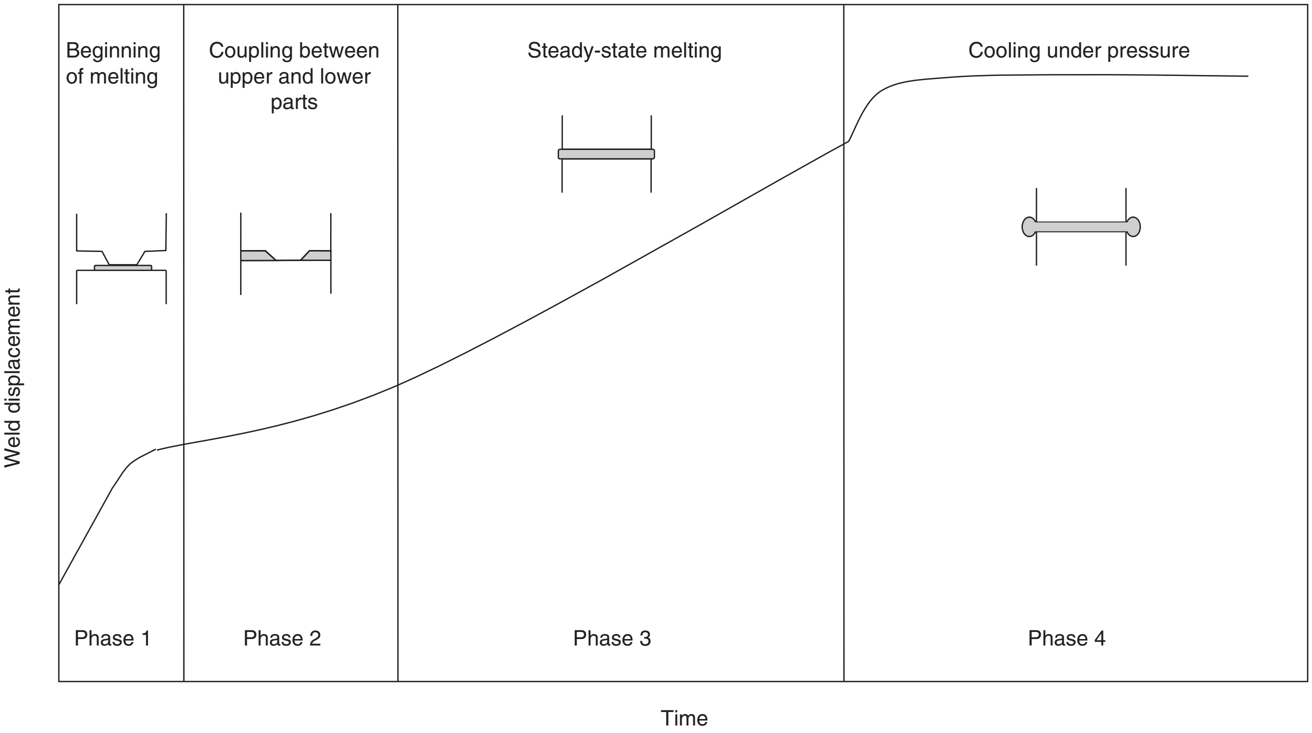


Figure 2.2. Stages of ultrasonic welding (Source: TWI Ltd).

with compact equipment. Welding times are shorter than in any other welding method, and there is no need for elaborate ventilation systems to remove fumes or heat. The process is energy efficient and results in higher productivity with lower costs than many other assembly methods. Tooling can be quickly changed, in contrast to many other welding methods, resulting in increased flexibility and versatility. It is commonly used in the healthcare industry because it does not introduce contaminants or sources of degradation to the weld that may affect the biocompatibility of the medical device.

A limitation of ultrasonic welding is that with current technology, large joints (i.e., greater than around 250 × 300 mm; 10 × 12 inches) cannot be welded in a single operation. In addition, specifically designed joint details are required. Ultrasonic vibrations can also damage electrical components, although the use of higher frequency equipment can reduce this damage. Also, depending on the parts to be welded, tooling costs for fixtures can be high [5–7].

2.3 Applications

Ultrasonic welding is used in almost all major industries in which thermoplastic parts are assembled in high volumes. Some examples are as follows:

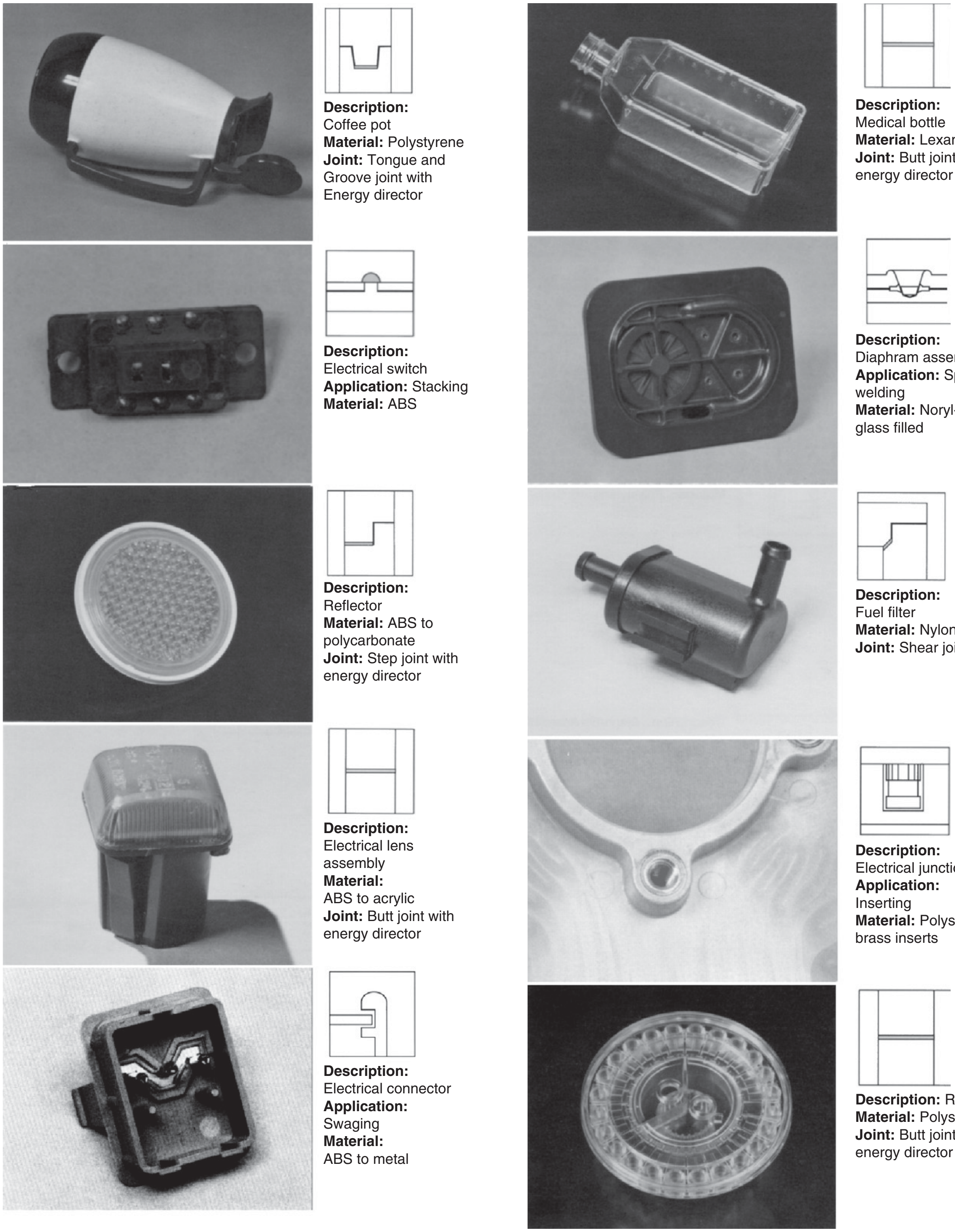
- Automotive: headlamp parts, dashboards, buttons and switches, fuel filters, fluid vessels, seat-belt locks, electronic key fobs, lamp assemblies, air ducts.
- Electronic and appliances: switches, sensors, data storage keys.
- Medical: filters, catheters, medical garments, masks [8].
- Packaging: blister packs, pouches, tubes, storage containers, carton spouts [9].

Some examples of ultrasonically welded items, together with the joint designs used are shown in Fig. 2.3.

2.4 Materials

2.4.1 Polymer Structure

Amorphous plastics have a random molecular structure and soften gradually over a broad temperature range (Fig. 2.4). They reach a glass transition state, then a liquid, molten state; solidification is also gradual, so that premature solidification is avoided. Amorphous polymers transmit ultrasonic vibrations efficiently and can be welded with a broad range of processing conditions.



Description: Coffee pot
Material: Polystyrene
Joint: Tongue and Groove joint with Energy director

Description: Electrical switch
Application: Stacking
Material: ABS

Description: Reflector
Material: ABS to polycarbonate
Joint: Step joint with energy director

Description: Electrical lens assembly
Material: ABS to acrylic
Joint: Butt joint with energy director

Description: Electrical connector
Application: Swaging
Material: ABS to metal

Description: Medical bottle
Material: Lexan
Joint: Butt joint with energy director

Description: Diaphram assembly
Application: Spot welding
Material: Noryl-30% glass filled

Description: Fuel filter
Material: Nylon 6-6
Joint: Shear joint

Description: Electrical junction box
Application: Inserting
Material: Polystyrene with brass inserts

Description: Rotor
Material: Polystyrene
Joint: Butt joint with energy director

Figure 2.3. Examples of ultrasonically welded items.

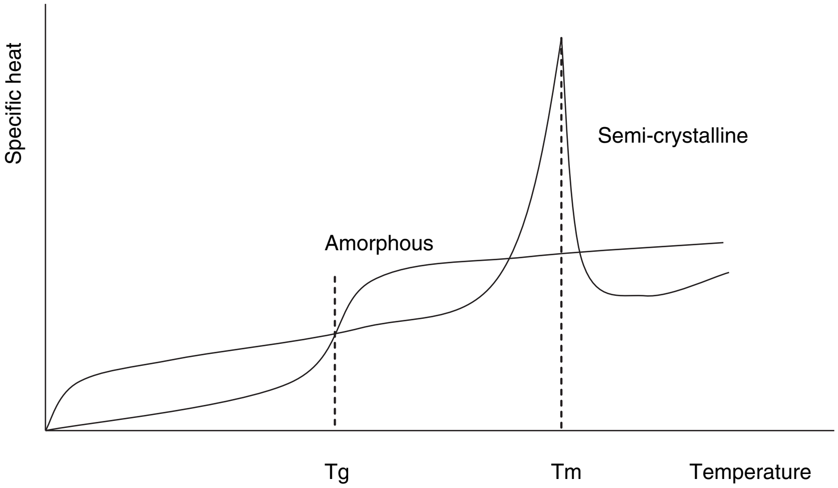


Figure 2.4. Specific heat of amorphous and semicrystalline polymers at the glass transition (T_g) and melting (T_m) temperatures (Source: TWI Ltd).

Hermetic seals are also easier to achieve with amorphous materials [10].

Semicrystalline plastics are characterized by regions of ordered molecular structure. High heat is required to disrupt this ordered arrangement. The melting point (T_m in Fig. 2.4) is sharp, and resolidification occurs rapidly as soon as the temperature drops slightly. The melt that flows out of the heated region of the joint therefore solidifies rapidly. When in the solid state, semicrystalline molecules are spring-like and absorb a large part of the ultrasonic vibrations, instead of transmitting them to the joint interface, so high amplitude is necessary to generate sufficient heat for welding [10].

2.4.2 Fillers and Reinforcements

Fillers (glass, talc, minerals) present in a thermoplastic can enhance or inhibit ultrasonic welding. Materials such as calcium carbonate, kaolin, talc, alumina trihydrate, organic filler, silica, glass spheres, calcium metasilicate (wollastonite), and mica increase stiffness of the resin and result in a better transmission of ultrasonic energy throughout the material at levels up to 20%, particularly for semicrystalline materials. At levels approaching 35%, insufficient thermoplastic resin may be present at the joint interface for reliable hermetic seals. At 40% filler content, fibers accumulate at the joint interface, and insufficient thermoplastic material is present to form a strong bond. Long glass fibers can cluster together during molding, so that the energy director can contain a higher percentage of glass than the bulk material. This problem can be eliminated by using short-fiber glass filler [7, 10, 11].

Abrasive particles present in many fillers cause horn wear when filler content exceeds 10%. The use of hardened steel or carbide coated titanium horns is recommended. Higher powered ultrasonic equipment may also be required to create sufficient heat at the joint [10].

2.4.3 Additives

Additives often increase the difficulty in achieving a good welded joint, even though they may improve the overall performance or the forming characteristics of the base material. Typical additives are lubricants, plasticizers, impact modifiers, flame retardants, colorants, foaming agents, and reground polymers.

Internal lubricants (waxes, zinc stearate, stearic acid, fatty acid esters) reduce the coefficient of friction between polymer molecules, resulting in a reduction of heat generation. However, this effect is usually minimal since the concentrations are low and they are dispersed within the plastic instead of being concentrated at the joint surface [10, 12].

Plasticizers, high-temperature organic liquids, or low-temperature melting solids impart flexibility and softness, and reduce the stiffness of the material. They reduce the intermolecular attractive forces within the polymer and interfere with the transmission of vibratory energy. Highly plasticized materials such as vinyl are very poor transmitters of ultrasonic energy. Plasticizers are considered internal additives, but they do migrate to the surface over time, making ultrasonic welding virtually impossible. Metallic plasticizers have a more detrimental effect than FDA-approved plasticizers [10].

Impact modifiers, such as rubber can reduce the material's ability to transmit ultrasonic vibrations, making higher amplitudes necessary to generate melting. Impact modifiers can also affect the weldability of the material by reducing the amount of thermoplastic material at the joint interface [10].

Flame retardants, inorganic oxides, or halogenated organic elements such as aluminum, antimony, boron, chlorine, bromine, sulfur, nitrogen, or phosphorus are added to resins to inhibit ignition or modify the burning characteristics of the material. For the most part, they are nonweldable. Flame retardants may comprise up to 50% or more of the total material weight, reducing the amount of weldable material in the part. High-power equipment, higher than normal amplitudes, and modification of the joint design to increase the amount of weldable material at the joint interface are necessary for welding these materials [10].

Most colorants (pigments or dyestuffs) do not inhibit ultrasonic energy transmission; however, they can cause the amount of weldable material available at the joint interface to be reduced. Titanium dioxide (TiO_2), used in white pigments, is inorganic and chemically inert. It can act as a lubricant and if used at levels greater than 5%, can inhibit weldability. Carbon black can also interfere with ultrasonic energy transmission through the material. The presence of colorants may require modification of processing parameters [10, 12].

Foaming agents reduce a resin's ability to transmit energy. Depending on the density, voids in the cellular structure interrupt energy flow, reducing the amount of energy reaching the joint area [10].

Welding materials with either high or varying amounts of regrind content should be carefully evaluated. Control of the quality and volume of regrind material in the parts to be welded is necessary for optimum welding. In some cases, 100% virgin material may be required.

2.4.4 Mold Release Agents

External mold release or parting agents (zinc stearate, aluminum stearate, fluorocarbons, silicones) applied to the surface of the mold cavity (usually by spraying) provide a release coating that facilitates part removal. Mold release agents can be transferred to the joint interface, where they lower the coefficient of friction of the material being welded, affecting heat generation at the joint interface, and interfering with the fusion of the melted surfaces. Furthermore, the chemical contamination of the resin by the release agent can inhibit the formation of a proper bond. Silicones have the most detrimental effect. External mold release agents can sometimes be removed with solvents. If it is necessary to use an external release agent, paintable/printable grades do not transfer to the molded part, but do prevent the resin from wetting the surface of the mold, and damaging effects of these grades on ultrasonic welding are lowest [10, 12].

2.4.5 Material Grades

Different grades of the same material may have different flow rates and different melt temperatures. One part may melt and flow but not the other, and no bond will form. For example, the cast grades of acrylic have higher molecular weights and melt temperatures, and are more brittle than the injection/extrusion grades; they are therefore more difficult to weld. Generally, both materials to be welded should have similar melt-flow rates (melt-flow rate gives an indication of molecular weight) and melt temperatures within 22°C (40°F) of each other. For best results, resins of the same grade should be welded [10, 12].

2.4.6 Moisture

Moisture content of a material can affect the strength of the weld. Hygroscopic materials such as polyester, polycarbonate, polysulfone, and especially nylon, absorb moisture from the air. When welded, the absorbed water will boil at 100°C (212°F); the trapped gas will create porosity and can degrade the plastic at the joint interface, resulting in a poor cosmetic appearance, a weak bond, and difficulty in obtaining a hermetic seal. For best results, such materials should be welded immediately after molding. If this is not possible, the parts should be kept dry-as-molded by storage in polyethylene bags. Special ovens can be used to dry the parts prior to welding; however, care must be taken to avoid material degradation.

2.4.7 Dissimilar Materials

In welding dissimilar materials, the melt temperature difference between the two materials should not exceed 22°C (40°F), and both materials should be similar in molecular structure. For large melt temperature differences, the lower-melting material melts and flows, preventing enough heat generation to melt the higher melting material. For example, if a high-temperature acrylic is welded to a low-temperature acrylic, with the energy director molded on the high-temperature part, the low-temperature part will melt and flow before the energy director, and bonds with poor strength may be produced. Only chemically compatible materials that contain similar molecular groups should be welded. Compatibility exists only among some amorphous plastics or blends containing amorphous plastics. Typical examples are ABS to acrylic, PC to acrylic, and polystyrene to modified PPO. Semicrystalline PP and PE have many common physical properties, but are not chemically compatible and cannot be welded ultrasonically [5, 10, 13].

Table 2.1 shows the material compatibility of some thermoplastics for ultrasonic welding.

2.5 Equipment

Equipment for ultrasonic welding consists of a power supply, a converter with booster attachment to increase or decrease the amplitude of vibration, a horn, fixtures or nests to support and align the parts being welded, and an actuator that contains the converter, booster, horn, and pneumatic controls (Fig. 2.5).

2.5.1 *Power Supply/Generator*

The power supply/generator converts the 50–60 Hz line voltage into a high voltage signal at the desired frequency (typically 20 kHz). The power supply/generator may include a built-in control module for setting weld programs and other functions.

Power supplies are available with varying levels of process control, from basic to microprocessor-controlled

Table 2.1. Polymer Compatibility for Ultrasonic Welding (Source: TWI Ltd)

	ABS	ABS/polycarbonate	Acetal	Acrylic	Cellulose acetate	ECTFE	LCP	Polyamide	PES	PPO	PC	PC/polyester	PBT	PET	PEEK	PEI	PE	PPS	PP	Polystyrene	Polysulfone	PVC	PTFE	PVDF	SAN
ABS	▨	▨		▨																O					O
ABS/polycarbonate	▨	▨		O							▨	O													
Acetal			▨																						
Acrylic	▨	O		▨							▨	O													O
Cellulose acetate					▨																				
ECTFE						▨																			
LCP							▨																		
Polyamide								▨																	
PES									▨																O
PPO										▨	O									▨					
PC		▨		▨						O	▨	O													
PC/polyester		O		O							O	▨	O												
PBT												O	▨												
PET														▨											
PEEK															▨										
PEI																▨									
PE																	▨								
PPS																		▨							
PP																			▨						
Polystyrene	O								▨											▨					O
Polysulfone																					▨				
PVC																						▨			
PTFE																							▨		
PVDF																								▨	
SAN	O			O					O											O					▨

▨ Compatible
O Some compatible

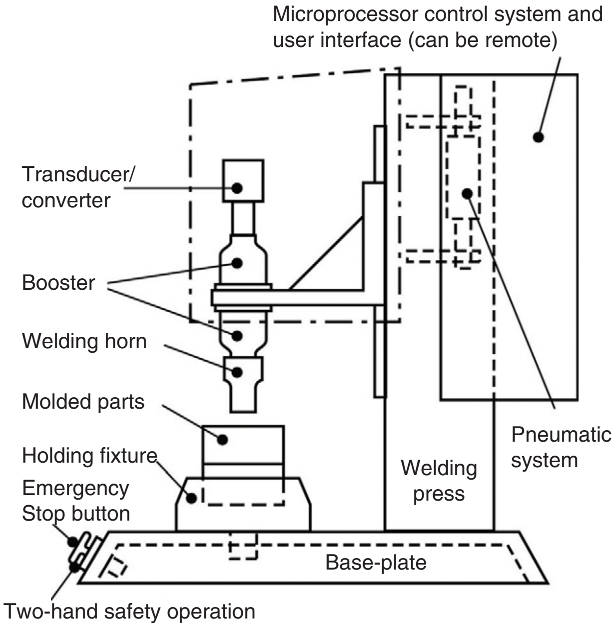


Figure 2.5. Components of an ultrasonic welder (Source: TWI Ltd).

units. Power output ranges from 100 to 6000 W. Controllers can operate at a constant frequency or, in newer models, the amplitude can be changed instantaneously during welding, in either a stepwise or a profile fashion. The actuator brings the horn into contact with the parts being welded, applies force, and retracts the horn when the welding is complete.

2.5.2 Transducer

The transducer, also known as the converter, is the key component of the ultrasonic welding system. The transducer converts the electrical energy from the generator to the mechanical vibrations used for the welding process. A schematic of the component is shown in Fig. 2.6.

The transducer consists of a number of piezoelectric ceramic (lead zirconate titanate, PZT) discs sandwiched between two metal blocks, usually titanium. Between each of the discs there is a thin metal plate, which forms the electrode. As the sinusoidal electrical signal is fed to the transducer via the electrodes, the discs expand and contract. Frequency of vibration can be in the range 15–70 kHz; however, the most common frequencies used in ultrasonic welding are 20 or 40 kHz. The amplitude or peak-to-peak amplitude is the distance the converter moves back and forth during mechanical vibrations. Typical values are 20 μm (0.0008 inches) for a 20 kHz converter and 9 μm (0.00035 inches) for a 40 kHz converter [12, 14].

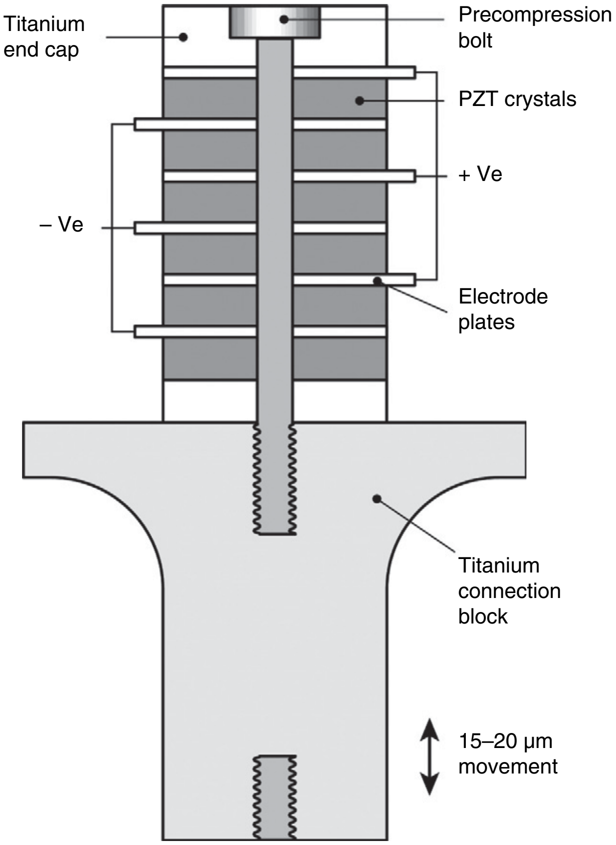


Figure 2.6. Diagram of an ultrasonic transducer (Source: TWI Ltd).

Since the piezoelectric discs have poor mechanical properties in tension, a bolt through the center of the device is used to precompress the discs. This ensures that the discs remain compressed as they expand and contract, that is, they have a mechanical offset bias.

2.5.3 Booster

The booster, also known as the booster horn, impedance transformer or amplitude transformer, is a machined part mounted between the converter and the horn to couple the ultrasonic vibrations from the converter to the horn. The primary purpose of the booster is to amplify the mechanical vibrations produced at the tip of the transducer. The secondary purpose is to provide a mounting point to attach the welding stack (transducer/booster/horn) to the actuator.

Boosters that change the amplitude are machined with different masses on either side of the booster's center or 'nodal' point (Fig. 2.7). The amplitude is increased when the lower-mass end is attached to the

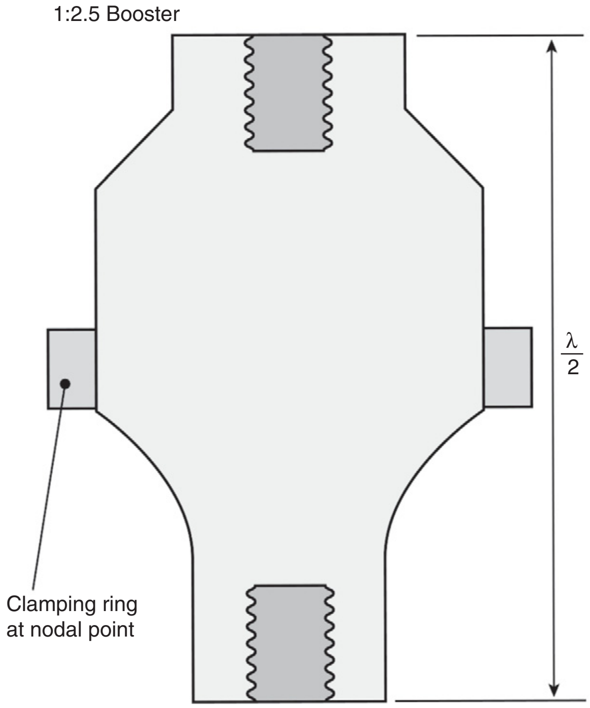


Figure 2.7. Schematic of a 1:2.5 booster (Source: TWI Ltd).

horn; conversely, the amplitude is decreased when the lower-mass end is attached to the converter. The magnitude of increase/decrease is proportional to the mass differences, expressed as a gain ratio. The gain ratios are usually marked on the booster or indicated by color coding (Fig. 2.8).

A metal ring around the center (nodal point) acts as the clamping point to the actuator, where the load can be transferred from the welding press to the components being welded.

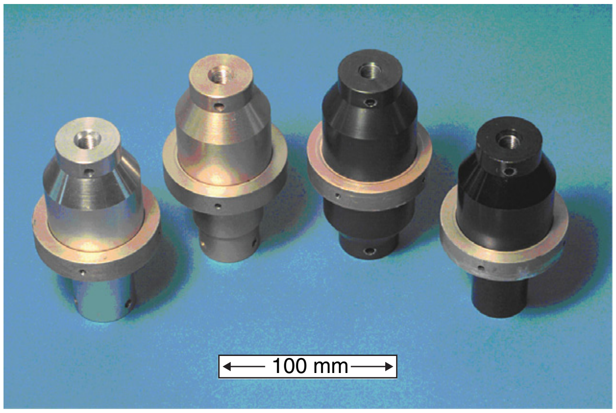


Figure 2.8. Examples of ultrasonic boosters (Source: TWI Ltd).

2.5.4 Horns

A welding horn, also known as a sonotrode, is an acoustical tool that transfers the mechanical vibrations to the workpiece, and is custom-made to suit the requirements of the application. The molecules of a horn expand and contract longitudinally along its length, so the horn expands and contracts at the frequency of vibration. The amplitude of the horn is determined by the movement from the longest value to the shortest value of the horn face in contact with the part (i.e., peak-to-peak movement). Horns are designed as long resonant bars with a half wavelength. By changing the cross sectional shape of a horn, it is possible to give it a gain factor, increasing the amplitude of the vibration it receives from the transducer–booster combination. Three common horn designs are the step, exponential, and catenoidal, as shown in Fig. 2.9.

Step horns consist of two sections with different but uniform cross-sectional areas. The transition between the sections is located near the nodal point. Due to the abrupt change in cross-section in the nodal plane, step horns have a very high stress concentration in this area and can fail if driven at excessive amplitude. Gain factors up to 9:1 can be attained with step horns.

Exponential horns have a cross-sectional area that changes exponentially with length. The smooth transition distributes the stress over a greater length, thus offering lower stress concentrations than that found in step horns. They generally have lower gain factors, so are used for applications requiring low forces and low amplitudes.

Catenoidal horns are basically step horns with a more gradual transition radius through the nodal point. They offer high gains with low stress concentrations.

Larger welding horns (typically greater than 90 mm (3.5 inches) in width or in diameter) have slots added to reduce general stress caused by horizontal vibrations. The slots, in effect, break large horns into smaller, individual horns, to ensure uniform amplitude on the horn face, and reduce internal stress (Fig. 2.10).

In applications where there are multiple welding operations taking place at the same time, a composite horn can be used. A composite horn is comprised of a large base, round or rectangular (half-wavelength), with half wave horns (usually stepped or circular) attached to it. It is important that the horn is acoustically balanced and is symmetrical.

A contoured horn is any standard shape horn with a specific part contour trace-milled into its contact surface. The contour is worked into the horn by copy-milling the part or digitally recording the part followed

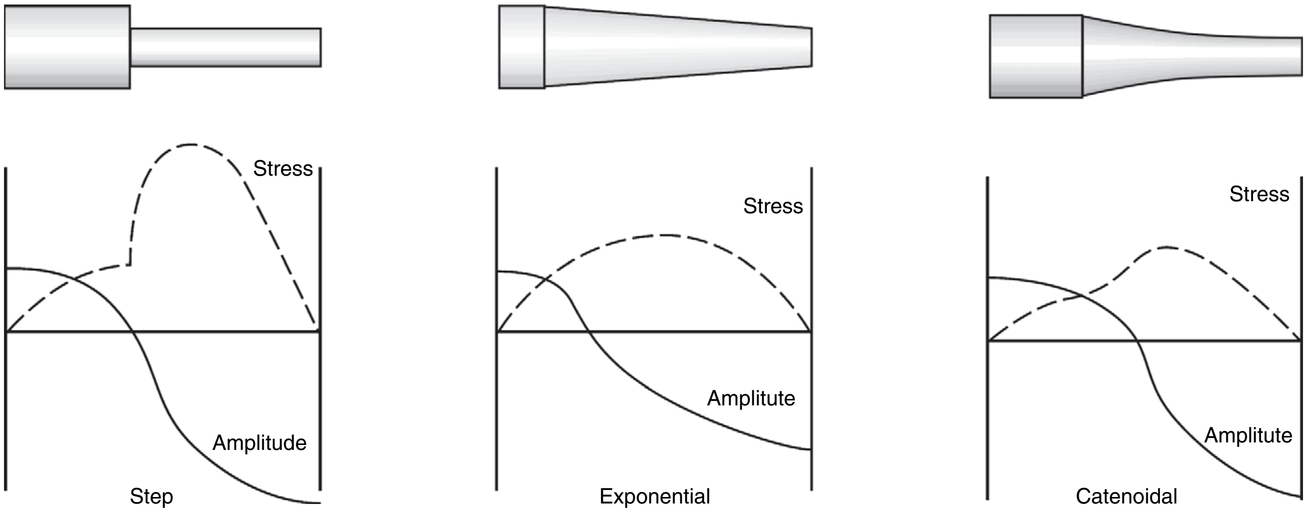


Figure 2.9. Step, exponential, and catenoidal welding horn profiles (Source: TWI Ltd).

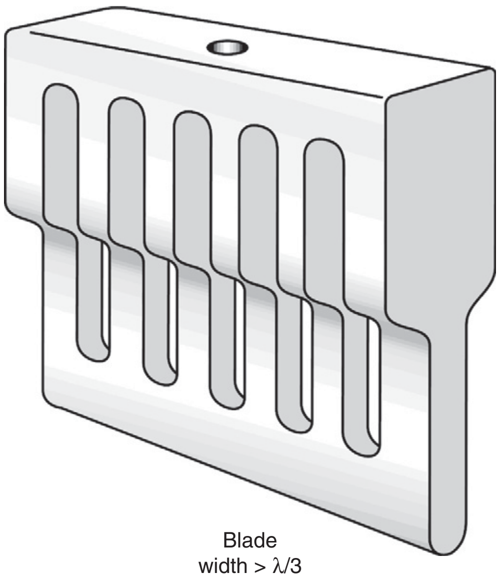


Figure 2.10. Slotted welding horn (Source: TWI Ltd).

by CNC milling. The horn must be thought of as a precision tuning fork; its shape should be as balanced and symmetrical as possible.

Horn materials are usually high-strength aluminum alloy, titanium, or hardened steel. Aluminum is a low-cost material which can be machined easily, and which has excellent acoustic properties. For these reasons, it is used for welding large parts and to make prototype horns or horns requiring complex machining. Aluminum may be inappropriate for long-term production applications due to its poor surface hardness and fatigue properties. However, it can be coated or plated with chrome or nickel to help alleviate these problems.

Titanium has good surface hardness and fatigue strength and excellent acoustic properties. However, it is very expensive and difficult to machine. Titanium may also be carbide-coated for high wear applications.

Steel horns can only be used for low amplitude applications due to its low fatigue strength. For severe wear applications such as ultrasonic metal inserting and welding glass filled materials, steel horns can be satisfactory.

Good horn design is a key to successful welding. Horns are precision parts that should only be manufactured by specialists who are adept in acoustical design and testing.

2.5.5 Actuator

The actuator, or welding press, houses the transducer, booster, and horn assembly (also known as the stack). Its primary purpose is to lower and raise the stack and to apply force on the workpiece in a controlled, repeatable manner.

2.5.6 Fixtures

Fixtures are required for aligning parts and holding them stationary during welding. Parts must be held in alignment with respect to the end of the horn so that uniform pressure between them is maintained during welding, and the process is repeatable. The fixture must also hold the parts stationary to transmit ultrasonic energy efficiently. Resilient fixtures and rigid fixtures are the two most common types.

Rigid fixtures (Fig. 2.11) are generally made of aluminum or stainless steel. They are normally used with semicrystalline materials or when welding flexible materials. Rigid fixtures should also be used for ultrasonic insertion, staking, spot welding, or swaging. Resilient fixtures (Fig. 2.12) are usually less costly to manufacture than rigid fixtures and are commonly made from poured or cast urethane. They are typically used for welding rigid amorphous materials. Resilient fixtures cause less part marking but also absorb more energy [5, 15].

Flatness or thickness variations in some molded parts, which might otherwise prevent consistent welding, may be accommodated by fixtures lined with elastomeric material. Rubber strips or cast- and cured silicone rubber allow parts to align in fixtures under normal static loads but act as rigid restraints under high-frequency vibrations. A rubber lining may also help absorb random vibrations which often lead to cracking or melting of parts at places remote from the joint area. PTFE, epoxy, cork, and leather have also been used as dampening materials [15].

Ease of loading and ejection are important considerations for fixtures.

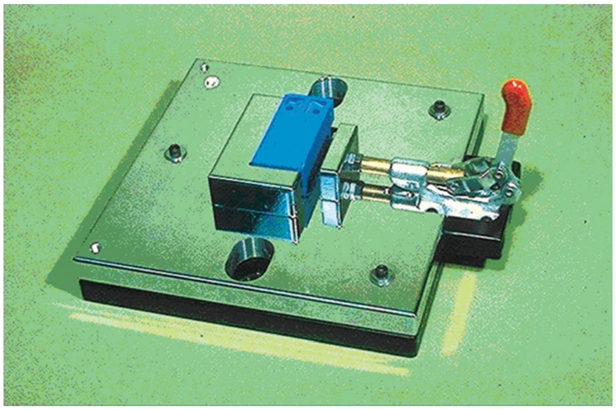


Figure 2.11. Rigid ultrasonic support with toggle clamp arrangement (Source: Branson Ultrasonics Corp.).

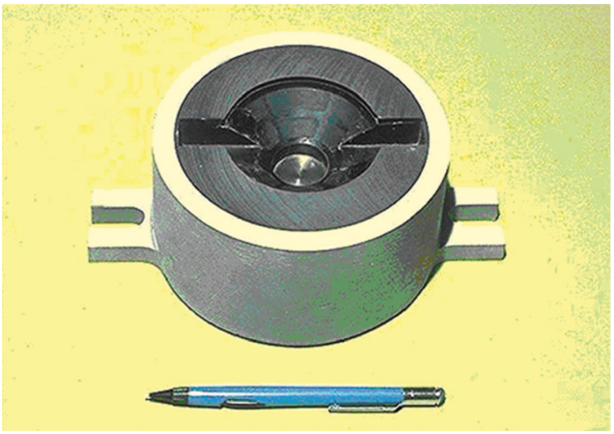


Figure 2.12. Resilient fixture (Source: Branson Ultrasonics Corp.).

2.5.7 Controls

Ultrasonic welding machines equipped with microprocessor-controlled power supplies can be operated in a time (or open-loop) mode, in which ultrasonic energy is applied for a particular time, or an energy or peak-power mode (closed-loop), in which power is monitored throughout the welding cycle and ultrasonic vibrations are terminated when a particular power level or energy level has been reached. Other welding modes possible with newer machines include welding to a predetermined displacement or distance traveled by the horn, and welding to a fixed finished part height [16].

On-screen monitoring of all process parameters is possible with microprocessor-controlled systems, in addition to programming of weld parameters and features for monitoring quality control (production counters, rejected parts counters, fault indicators). Welders with microprocessors perform self-diagnostics, and can be automated and integrated into external production lines [7, 12, 13].

2.5.8 Machine Types

A number of different welding machine configurations are available, depending on the intended scope of operation. An integrated machine (Fig. 2.13) contains all the equipment in a one-piece unit and usually requires just a connection to compressed air and power to become operational. Such machines are most commonly used for manual load and unload welding application. A component system is assembled from interchangeable power supplies, actuators and stands, and is customized for each specific application. A handheld system (Fig. 2.14) consists of a power supply and converter designed to be held by the operator. They are used in simple applications where consistency and appearance are not particularly important, such as spot welding of sheet. The power supply contains all the controls and monitoring devices, except for the manually operated trigger switch that is mounted on the converter.

Figure 2.13. Integrated ultrasonic welding machine (Source: Branson Ultrasonics Corp.).

The typical cost for either an integrated unit or a component system that includes a power supply and actuator (without tooling) is $12,000–$60,000 (US dollars).

2.6 Joint Design

Selection of the joint design must be considered early in the part design stage. The product designer should ask the following questions before choosing the type of joint design the product will need:

- What is the material to be used?
- What are the final requirements of the assembly?
- Is a structural bond necessary, and what load forces does it need to sustain?

Figure 2.14. Handheld ultrasonic welding system (Source: Branson Ultrasonics Corp.).

- Is a hermetic seal required?
- What are the cosmetic requirements of the assembly?
- Is outward or inward flash objectionable?

Joint design is crucial for optimal results in ultrasonic welding. It depends on the type of thermoplastic, part geometry, and end-use requirements. Designs for ultrasonic welding should have a small initial contact area between the parts to be welded, to concentrate the ultrasonic energy and decrease the total time needed for melting. Mating parts should be aligned and in intimate contact, but should be able to vibrate freely in relation to each other in order to create the required friction for welding. Mating surfaces should be uniform, and the surface in contact with the horn should be large enough to prevent its sinking into the plastic during vibration [5, 17].

For optimal welding, the joint interface should be in a single plane that is parallel to the contacting surface of the horn; ultrasonic energy then travels the same distance to all points in the weld, and a uniform weld is produced. In addition, the part surface in contact with the horn should be in a single plane parallel to the joint interface. Several unfavorable joint designs are shown in Fig. 2.15.

Flat, parallel mating surfaces are especially important if hermetic seals are desired; hermetic seals are easier to achieve with amorphous materials [5, 17].

2.6.1 Energy Directors

An energy director is a raised triangular ridge of material molded on one of the joint surfaces (Fig. 2.16). The apex of the energy director is under the greatest stress during welding and is forced into contact with the other part, generating friction, which causes it to melt. The molten energy director flows into the joint interface and forms a bond. Energy directors are well-suited for amorphous materials, since they flow and solidify gradually; the strength of welds in semicrystalline materials obtained with energy directors is not as high. Energy directors ensure that a specific volume of material is melted to produce good bond strength without excessive flash. They do not provide part alignment or control flash.

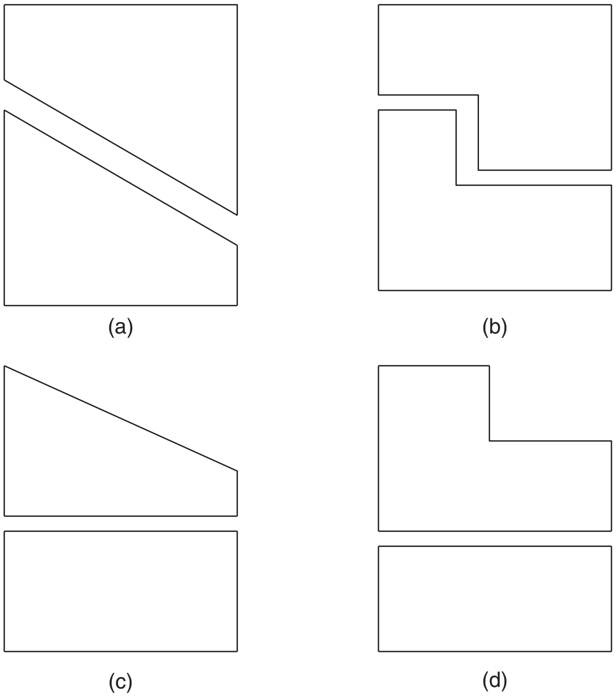


Figure 2.15. Unfavorable joint designs: (a) joint interface is in a single plane but not parallel to the horn contact surface; (b) joint interface is not in a single plane; (c) horn contact surface is not parallel to the joint interface; (d) horn contact surface is not in a single plane (Source: TWI Ltd).

A general recommendation is that for most amorphous materials, the apex of the energy director should be at a 90° angle and have a height 50%–65% of the width of the base. Size ranges from 0.127–0.762 mm (0.005–0.030 inches) high and from 0.254–1.53 mm (0.010–0.060 inches) wide. For semicrystalline materials it is recommended that the apex should be at a 60° angle, with a height of 85% of the width of the base. Base width ranges from 0.254–1.27 mm (0.010–0.050 inches).

The steeper angle and sharper point of energy directors for semicrystalline materials causes the energy director to partially embed itself into the mating surface during the early stages of welding, reducing premature solidification and degradation due to air exposure. A higher bond strength is obtained, and the chances of obtaining a hermetic seal are increased. This design also provides superior results with polycarbonate and acrylic [5].

Various joint designs are used with energy directors. The butt joint (Fig. 2.17) is one of the simplest and most common designs. Because butt joints do not self-align, fixtures are necessary for part alignment. Hermetic seals in amorphous materials can be obtained with butt joints, as long as the mating surfaces are almost perfectly flat with respect to one another. Hermetic seals with butt joints are difficult to achieve with semicrystalline polymers because the melt is exposed to air during welding, which can accelerate crystallization and cause oxidative degradation of the melt, resulting in brittle welds [5, 14].

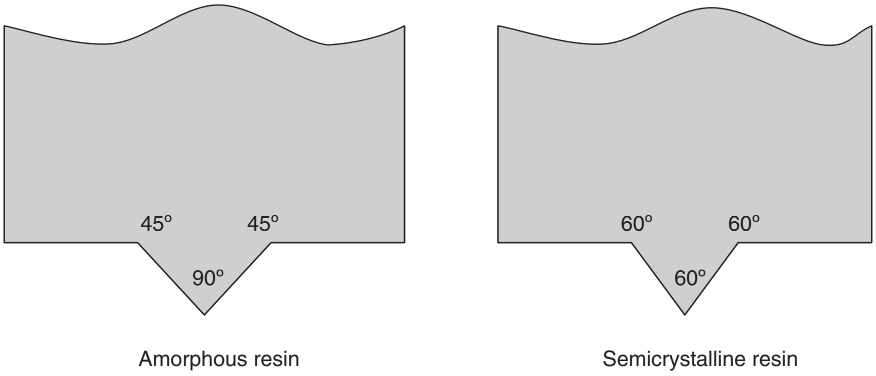


Figure 2.16. Energy directors for amorphous and semicrystalline materials (Source: TWI Ltd).

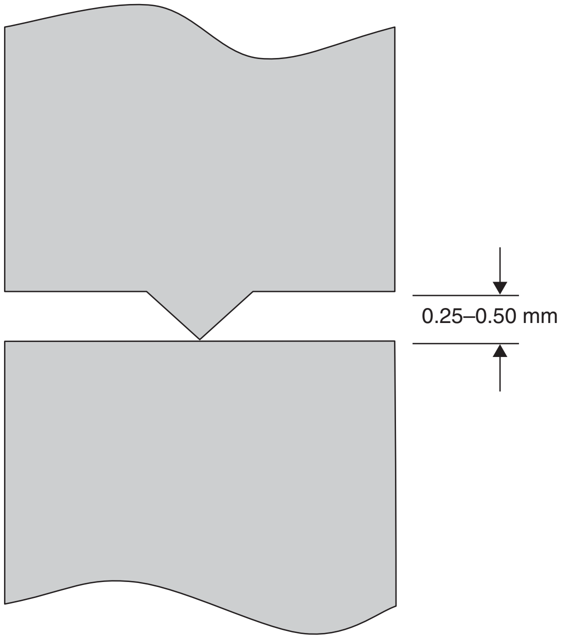


Figure 2.17. Butt joint with energy director (Source: TWI Ltd).

A modification of the energy director joint design consists of many small surface projections molded into the joint surface opposite the energy director (Fig. 2.18). The textured surface, typically 0.0765–0.152 mm (0.003–0.006 inches) deep, enhances surface friction by preventing side-to-side movement of the energy director, and peaks and valleys formed by texturing form a barrier that prevents melt from flowing out of the joint area. Flash is reduced, and a greater surface area is available for bonding. Weld strengths of up to three times that of an untextured surface are possible, and the total energy required for welding is reduced [18].

The step joint with energy director (Fig. 2.19) eliminates flash on the exterior of the joint, and is useful when cosmetic appearance is important. The generated flash flows into a clearance gap or groove provided in the joint, which is slightly deeper and wider than the tongue. Welds with good shear and tension strength are produced. Because only part of the wall is involved in bonding, step joints are sometimes considered to produce lower strength welds than butt joints with energy directors. The recommended minimum wall thickness is 2.03–2.29 mm (0.080–0.090 inches) [5, 14].

The depth of the groove should be 0.13–0.25 mm (0.005–0.01 inches) greater than the height of the tongue, leaving a slight gap between the finished parts. This is done for cosmetic purposes so that it will not be

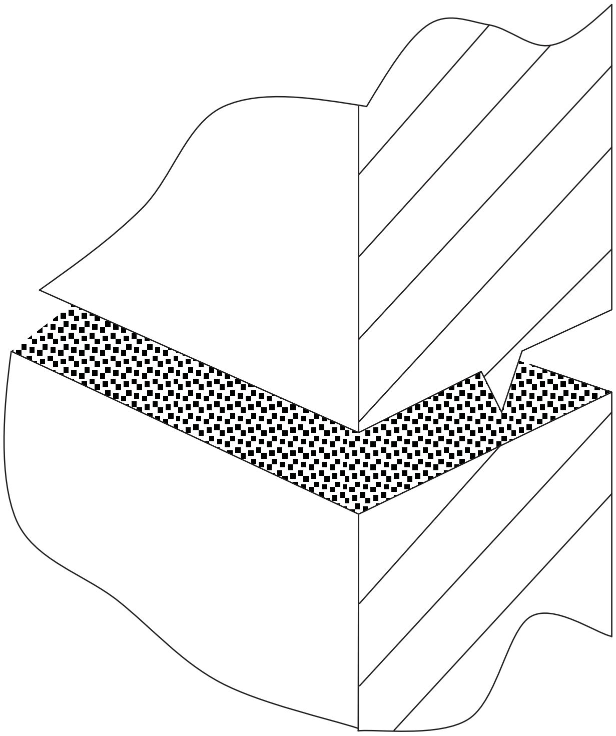


Figure 2.18. Energy director with textured surface on mating part (Source: TWI Ltd).

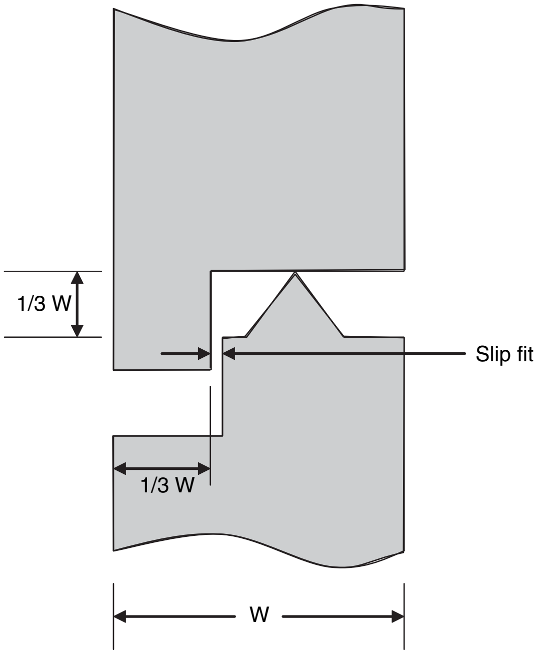
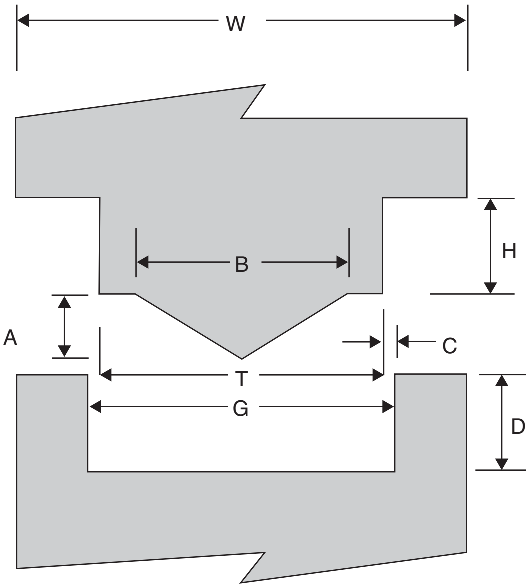


Figure 2.19. A step joint with energy director (Source: TWI Ltd).



W = Wall thickness
A = Energy director height
B = Energy director base width
H = Tongue height
T = Tongue width
C = Clearance
G = Groove width
D = Groove depth
B = W/4 to W/5
A = B × 0.5 (amorphous)
A = B × 0.866 (semicrystalline)
H = W/3
T = W/3
C = 0.05 to 0.10 mm
G = T + (0.1 to 0.2 mm)
D = H – (0.13 to 0.25 mm)

Figure 2.20. Tongue and groove joint with energy director (Source: TWI Ltd).

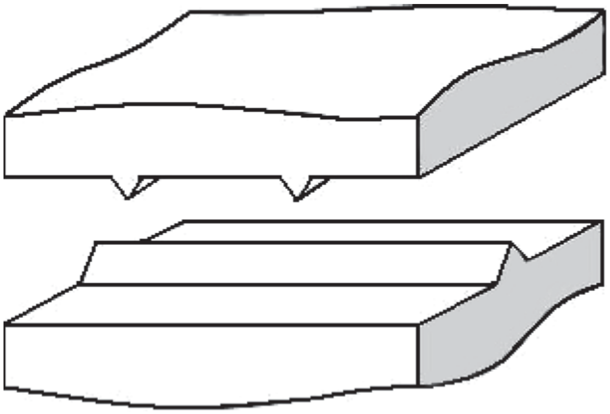


Figure 2.21. Criss-cross energy director design (Source: TWI Ltd).

obvious if the surfaces are not perfectly flat, or the parts are not perfectly parallel. The width of the groove is 0.05–0.10 mm (0.002–0.004 inches) larger than that of the tongue, leaving a slight gap between the finished parts.

In the tongue and groove joint (Fig. 2.20) the melt is completely enclosed in a groove in the joint, which is slightly larger (0.05–0.10 mm; 0.002–0.004 inches) than the tongue. It is used to prevent flash when cosmetic appearance is important, and aligns the parts so that additional fixtures are not necessary. It produces a low pressure hermetic seal. Close tolerances required in this joint make parts more difficult to mold, and relatively large wall thicknesses are necessary. Minimum wall thickness is 3.05–3.12 mm (0.120–0.125 inches). The energy director is dimensionally identical to the one used for the butt joint [5, 17].

Other joint designs with energy directors are less common. In the criss-cross joint (Fig. 2.21), energy directors are present on both mating surfaces and are perpendicular to each other. This design provides minimum initial contact at the interface with a potentially larger volume of material involvement in welding. The size of the energy director should be about 60% of a standard energy director design.

A cone design (Fig. 2.22) reduces the overall area to be welded, and requires less energy and weld time. It requires minimum heat generation which is important in preventing shrinkage, but it results in lower structural strength.

Interrupted energy directors (Fig. 2.23) are used to reduce the overall weld area; they require less energy and result in structural welds. Energy directors can also be perpendicular to the wall, to gain resistance to peeling forces (Fig. 2.24).

2.6.2 Shear Joints

The shear joint (Fig. 2.25) is used in welding semicrystalline materials that have a sharp and narrow melting point. Energy directors are not as useful with crystalline materials, because material displaced from the energy director either degrades or recrystallizes before it can flow across the joint interface and form a weld. The small, initial contact area of the shear joint is the first to melt during welding; melting then continues

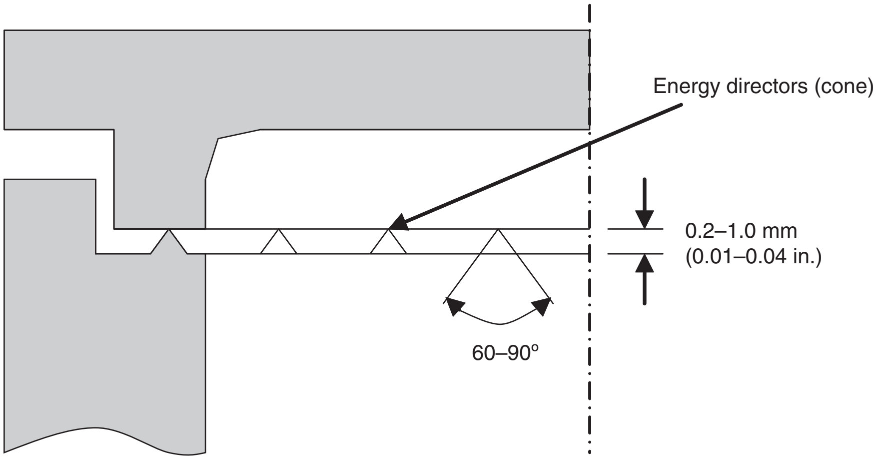


Figure 2.22. Cone energy director design (Source: TWI Ltd).

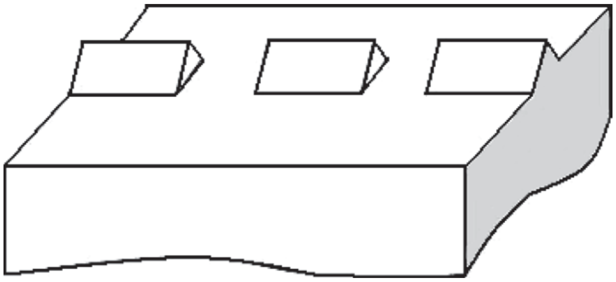


Figure 2.23. Interrupted energy directors (Source: TWI Ltd).

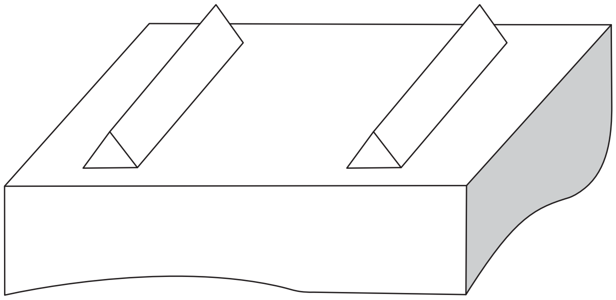
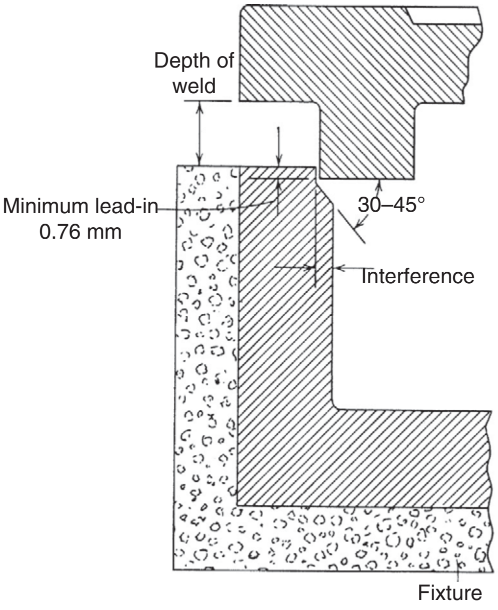
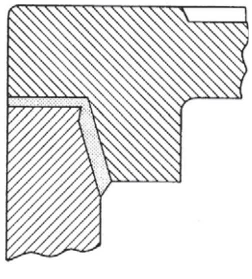


Figure 2.24. Energy director design with energy directors perpendicular to the joint interface (Source: TWI Ltd).





Typical interferance for shear joint

Maximum part dimension	Interferance per side
19 mm or less	0.20–0.30 mm
19–38 mm	0.30–0.41 mm
38 mm or more	0.41–0.51 mm

Figure 2.25. Shear joint design.

along the vertical walls as the parts telescope together in a smearing action that eliminates exposure to air and premature solidification. Strong hermetic seals can be obtained. Rigid side-wall support is necessary to prevent deflection during welding. The top part of the joint should be as shallow as possible, similar to a lid, but of sufficient structural integrity to withstand internal deflection. Shear joints provide part alignment and a uniform contact area [5, 17].

Higher energy is necessary when using shear joints with semicrystalline materials, due to the greater melt area and the high energy required for melting crystalline materials. This requires either longer weld times (up to 3–4 times longer than other joints) or greater power (3000 W instead of 2000 W) and greater amplitudes. Shear joints are useful for cylindrical parts, but do not work as well with rectangular parts in which the walls tend to oscillate perpendicular to the weld axis, or with flat, round parts that are subject to hoop stress. Hermetic seals and high weld strengths can be produced with shear joints in parts with square corners or rectangular designs, but substantial amounts of flash will be visible on the upper surface after welding [17, 19].

Shear joint modifications for large parts or for parts in which the top part is deep and flexible are shown in Fig. 2.26. When flash is unacceptable, traps can be incorporated into the shear joint design (Fig. 2.27).

2.6.3 Part Design Considerations

Since sharp corners localize stress, parts with sharp corners may fracture or melt when ultrasonic vibrations are applied. Appendages, tabs, or other protrusions also localize stress and may fall off during welding. To avoid this, a generous radius should be allowed on all the corners and edges, and areas where appendages join the main part. To further minimize stress on appendages, the use of a 40 kHz frequency, the application of light force, or thicker appendages are recommended.

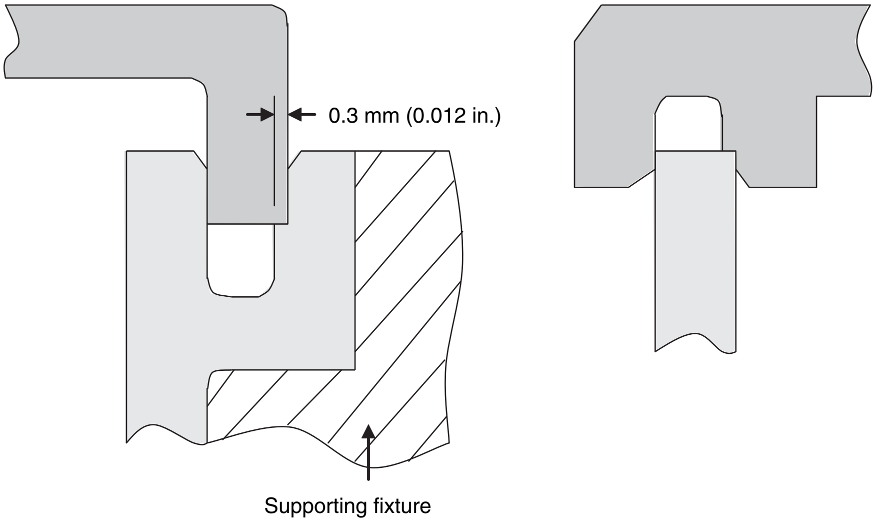


Figure 2.26. Shear joint modifications for large parts (Source: TWI Ltd).

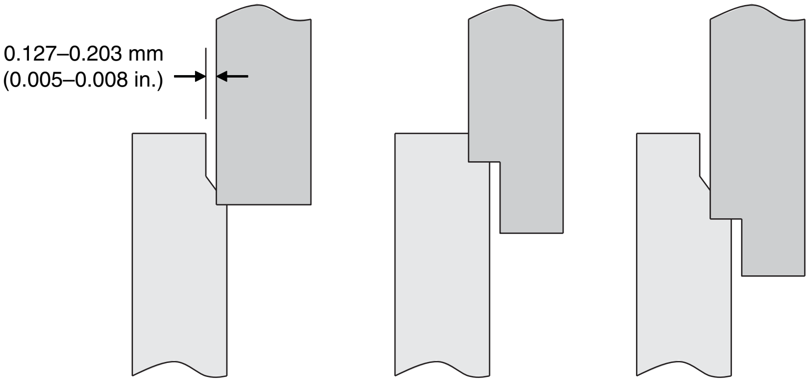


Figure 2.27. Shear joint modifications incorporating flash traps (Source: TWI Ltd).

Energy does not travel well around holes, voids, or bends and little or no welding will occur directly beneath these areas, depending on the type of material and size of the feature. Where possible, all sharp angles, bends, and holes should be eliminated.

Thin sectioned, flat, circular parts may flex or "diaphragm" during welding. The horn may bend up and down ("oil canning" effect) when it contacts the part, and intense heat from the flexing may cause the horn to melt or burn a hole through the material. Diaphragmming often occurs in the center of the part or in the gate area; making these sections thicker may therefore prevent it [5].

2.7 Welding Parameters

Important processing parameters in ultrasonic welding are weld time, (the time vibrations are applied), weld pressure or force, hold time (the time allowed for cooling and solidification after vibration has ceased), hold force, trigger force (the force applied to the part before ultrasonic vibrations are initiated), power level, and amplitude of vibration. The horn must be properly positioned in contact with the top part before ultrasonic vibrations are initiated; welding cannot be performed successfully if the horn contacts the part after vibrations have begun.

2.7.1 Frequency

Most ultrasonic welding equipment operated at 20 kHz until the early 1980s; 30 and 40 kHz frequencies are now common, in addition to low frequency (15 kHz) equipment for semicrystalline materials. Advantages of higher frequency equipment include less noise, smaller component size (the tooling of 40 kHz welders is one-half the size of units operating at 20 kHz), increased part protection due to reduced cyclic stressing, and indiscriminate heating in regions outside the joint interface, improved control of mechanical energy, lower welding forces, and faster processing speeds. Disadvantages include reduced power capability due to the small component size and difficulty in performing far-field welding due to the reduction in amplitude. Higher frequency ultrasonic machines are generally used for small, delicate components such as electrical switches [7, 13, 20, 21].

With 15 kHz welders, most thermoplastics can be welded faster and, in most cases, with less material degradation than with 20 kHz. Parts marginally welded at 20 kHz, especially those fabricated from the high performance engineering resins, can be effectively welded at 15 kHz. At these lower frequencies, horns have a longer resonant length and can be made larger in all dimensions. Another important advantage of using 15 kHz is that there is significantly less attenuation through the thermoplastic material, permitting the welding of many softer plastics, and at greater far field distances than possible using higher frequencies [22].

2.7.2 Weld Time

The weld time is the length of time the horn vibrates per weld cycle, and usually equals the time the horn is actually contacting the part. The correct time for each application is determined by trial and error. Increasing the weld time generally increases weld strength until an optimal time is reached; further increases result in either decreased weld strength or only a slight increase in strength, whilst at the same time, increasing weld flash and the possibility of marking the part.

2.7.3 Weld Pressure/Force

Weld pressure provides the static force necessary to 'couple' the welding horn to the parts so that vibrations may be introduced into them. This same static load ensures that parts are held together as the molten material in the weld solidifies during the 'hold' portion of the welding cycle. Determination of optimum pressure is essential for good welding.

Weld pressures that are too low generally result in poor energy transmission or incomplete melt flow, leading to long weld cycles. Increasing either the weld force or pressure decreases the weld time necessary to achieve the same displacement. If pressure is too high, the greater melt volume results in molecular alignment in the flow direction and decreased weld strength, as well as the possibility of part marking. In extreme cases, if the pressure is high in relation to the horn tip amplitude, it can overload and stall the horn.

Most ultrasonic welding is performed at a constant pressure or force. On some systems, the force can be altered during the cycle. In force profiling, weld force is decreased during the time that ultrasonic energy is applied to the parts. Decreased weld pressure or force later in the weld cycle reduces the amount of material squeezed out of the joint, allows more time for intermolecular diffusion, reduces molecular orientation, and increases weld strength. For materials like polyamide, which have a low melt viscosity, this can significantly improve weld strength.

2.7.4 Amplitude

In ultrasonic welding using energy directors, the average heating rate (Q_{avg}) is dependent on the complex loss modulus of the material (E''), the frequency (ω), and the applied strain (ε_o):

$$Q_{avg} = \omega \varepsilon_o^2 E''/2$$

The complex loss modulus of the thermoplastic is strongly temperature-dependent, so that as the melt or glass transition temperature is approached, the loss modulus increases, and more mechanical energy is converted to thermal energy. Temperature at the weld interface rises rapidly (over 1000°C/sec or 1800°F/sec) after heating is initiated [23].

The applied strain is proportional to the vibrational amplitude of the horn, so that heating of the weld interface can be controlled by varying the amplitude of vibration. Amplitude is an important parameter in controlling the squeeze flow rate of the thermoplastic. At high amplitudes, the weld interface is heated at a higher rate; temperature increases, and the molten material flows at a higher rate, leading to increased molecular alignment, significant flash generation, and lower weld strength. High amplitudes are necessary to initiate melting. Amplitudes that are too low produce nonuniform melt initiation and premature melt solidification [23].

As amplitude is increased, greater amounts of vibrational energy are dissipated in the thermoplastic material, and the parts being welded experience greater stress. In using constant amplitude throughout the welding cycle, the highest amplitude that does not cause excessive damage to the parts being welded is generally used. For semicrystalline polymers such as PE and PP, the effect of amplitude of vibration is much greater than for the amorphous polymers such as ABS and polystyrene. This is probably due to the greater energy required for melting and welding of the semicrystalline polymers.

The amplitude can be adjusted mechanically by changing the booster or horn, or electrically by varying the voltage supplied to the converter. In practice, large amplitude adjustments are made mechanically, while fine adjustments are made electrically. High-melt-temperature materials, far-field welds and semicrystalline materials generally require higher amplitudes than do amorphous materials and near-field welds.

Typical peak-to-peak amplitude ranges are 30–100 μm (1.2–3.9 mil) for amorphous plastics, and 60–125 μm (2.4–4.9 mil) for crystalline plastics.

Amplitude profiling, in which the amplitude is decreased during the welding cycle has been used to achieve good melt flow and consistent, high weld strengths.

With combined amplitude and force profiling, high amplitudes and forces are used to initiate melting, which are then decreased to reduce molecular alignment with the weld line.

2.7.5 Process Control

Most ultrasonic welding machines nowadays feature fully programmable, microprocessor control to program and monitor all welding parameters. Some machines monitor and adjust the entire process every millisecond. The controller takes 1000 actual reference weld measurements per second, providing true quality control. The welding modes of time, energy, or distance can be selected from the controller.

Welding by time is the most basic mode of operation. The components are preassembled in the fixture and the horn brought into contact with the upper part, whilst the ultrasound is activated for the designated time. The power drawn from one cycle to the next can be monitored to give some indication of weld quality, and if it falls outside a range, alarms signals can warn of a potentially defective weld.

Welding by energy is based upon closed feedback control, that is, the machine monitors the power drawn as the weld cycle progresses and terminates the weld once the set energy is delivered.

In welding by distance, a linear encoder mounted to the actuator accurately measures either the weld collapse or total distance traveled by the welding horn, allowing components to be joined by a specific weld depth. This mode operates independent of time or energy and compensates for any tolerance variation in the molded parts, giving the best guarantee that the same amount of material in the joint is melted each time.

2.8 Variants of Ultrasonic Welding

2.8.1 Ultrasonic Spot Welding

Ultrasonic spot welding joins two thermoplastic parts at localized points without a preformed hole or energy director. It produces a strong structural weld, and is especially suitable for large parts or parts with complicated geometry or hard-to-reach joining surfaces. Spot welding lends itself to sheets of extruded or cast thermoplastic and is often used on vacuum-formed parts, such as blister (clamshell) packaging.

In spot welding, the horn has a pilot tip, which melts through the top part and into the bottom part to a predetermined depth, when ultrasonic vibrations are applied. When vibrations cease, the melt from both parts flow together, forming a weld with the top side having a raised ring produced by the welding tip (Fig. 2.28). The bottom layer of a spot welding joint has a smooth appearance. Spot welding can be performed with hand-held guns, single- or double-headed bench welders, or with 'gang welding' systems composed of many spot welding heads that perform several welding operations simultaneously [5, 7, 12, 24].

Guidelines for spot welding include a rigid support directly under the spot weld area to prevent marking; medium to high amplitude to ensure adequate material penetration; and low pressure to ensure adequate melt at the joint interface.

2.8.2 Ultrasonic Welding of Fabrics and Films

Fabrics and films used across a range of industries such as the medical, packaging, and textile industries can be welded using ultrasonic energy. Continuous ultrasonic bonding and plunge mode processing are described here.

In continuous ultrasonic bonding (Fig. 2.29), two or more material layers are assembled by passing them through a gap between a vibrating horn and a rotary drum or anvil. The rotary drum is usually made out of hardened steel and has a pattern of raised areas machined into it. Ultrasonic vibrations and compression between the horn and the drum create frictional heat at the point where the horn contacts the materials. Bonding occurs only at these points, creating softness, breathability, and absorption in the bonded materials. These properties are important for hospital gowns, sterile garments, diapers, and other applications used in clean room environments and the medical industry. Ultrasonic bonding uses much less energy than thermal bonding, which uses heated rotary drums to bond materials together [5].

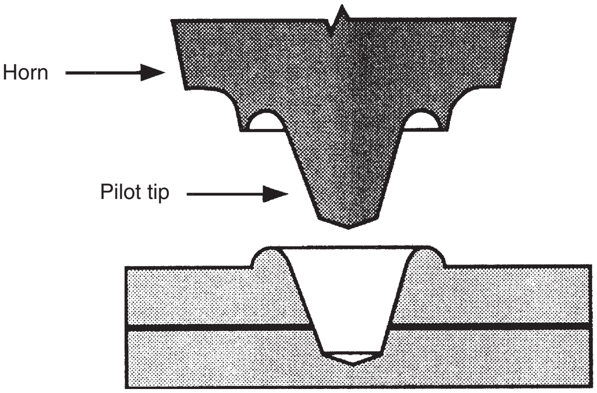


Figure 2.28. Ultrasonic spot welding.

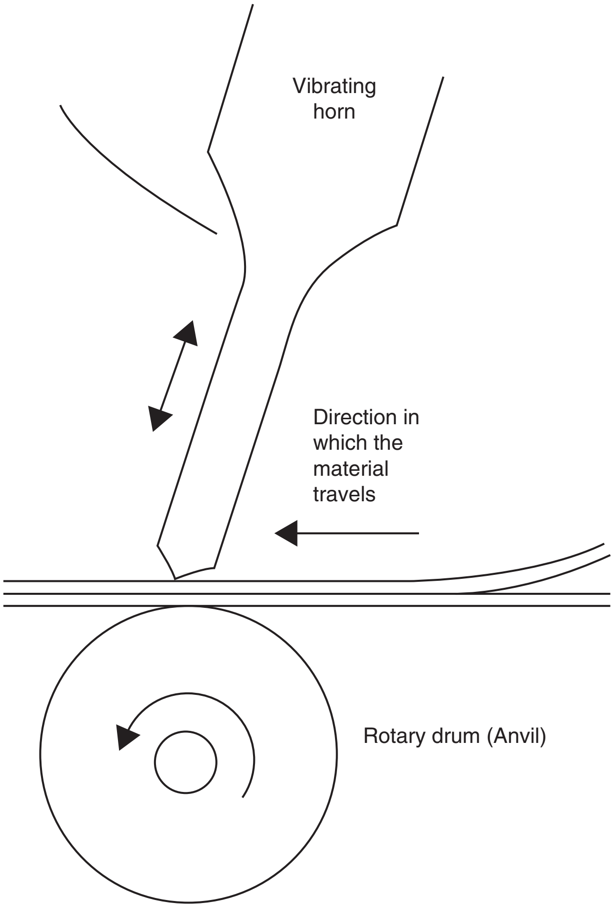


Figure 2.29. Ultrasonic bonding.

In the plunge-mode process, the material remains in a fixed location and is periodically contacted by the ultrasonic horn (Fig. 2.30). Either the horn face or the anvil will incorporate a pattern to focus the ultrasonic energy and produce a melt. The horn may also be adapted to perform a cut-seal operation. Typical plunge applications include filters, strapping, buckles, belt loops, bra straps, and vertical blinds.

The fabrics and films best suited to ultrasonic welding contain thermoplastic materials with similar melting points and compatible molecular structure. Favorable characteristics include a uniform thickness, high coefficient of friction, and a minimum 65% thermoplastic content. The actual structure of the material also has a significant effect on the weldability. Major categories of thermoplastic textiles and films are wovens,

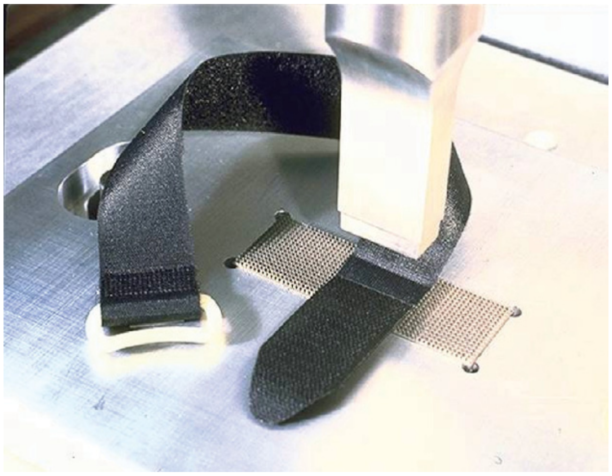


Figure 2.30. Plunge-mode welding of fabrics (Source: Branson Ultrasonics Corp.).

nonwovens, knits, films, coated materials, and laminates. Factors such as yarn density, tightness of weave, elasticity, and style of knit can all have an influence on the success of ultrasonic welding.

Thermoplastic fabric and films made of polyester, nylon, PP, and PE are all suitable for ultrasonic processing.

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3 Vibration Welding

3.1 Process Description

Vibration welding uses heat generated by friction at the interface of two materials to produce melting in the interfacial area. The molten materials flow together under pressure, forming a weld upon cooling. Vibration welding can be accomplished in a short time (1–10 seconds cycle time) and is applicable to a variety of thermoplastic parts with planar or slightly curved surfaces.

The two main types of vibration welding are: linear, in which friction is generated by a linear, reciprocating motion (Fig. 3.1), and orbital, in which the upper part to be joined is vibrated in a circular motion. Linear vibration welding is most commonly used, but orbital vibration welding makes the welding of irregularly shaped plastic parts possible.

Process parameters are the amplitude and frequency of vibration, weld pressure, and weld time, all of which affect the strength of the resulting weld.

The welding process consists of four phases (Fig. 3.2). In Phase I, the heat generated through friction raises the temperature of the interfacial area to the glass transition temperature of amorphous thermoplastics or the melting point of semicrystalline plastics. Since the material is still in the solid state, there is no displacement (penetration)—the distance through which the parts approach each other during welding due to lateral flow of molten material—in this phase. In Phase II, material at the interface begins to melt and flow in a lateral direction, causing an increase in weld displacement. In Phase III, the rate of melt generation equals the rate of melt displacement, which therefore increases linearly with time. At the end of Phase III, the vibratory motion is stopped, and during Phase IV, the weld penetration increases slightly as the molten film solidifies under pressure.

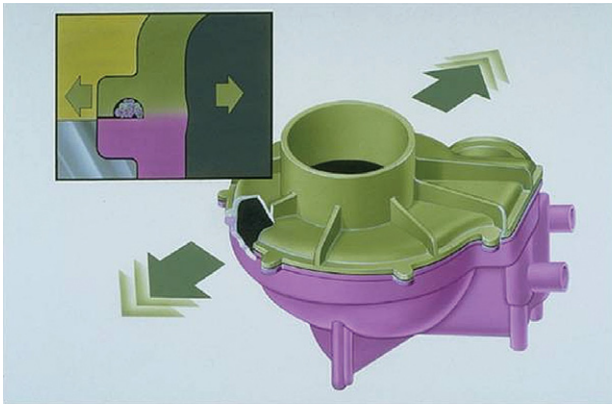

Figure 3.1. Linear vibration welding (Source: Branson Ultrasonics Corp.).

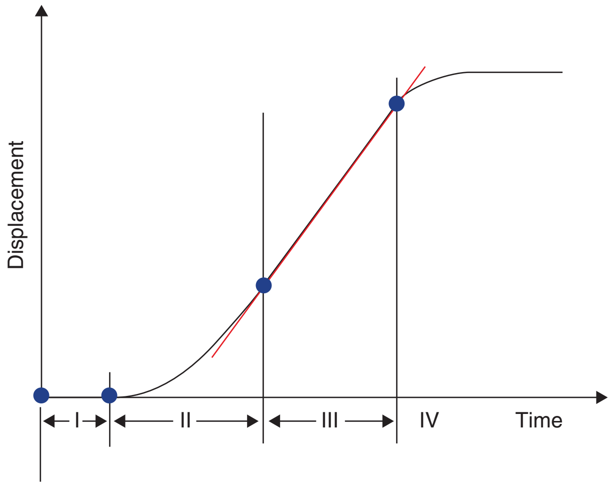

Figure 3.2. Displacement versus time curve showing the four phases of vibration welding (Source: TWI Ltd).

3.2 Advantages and Disadvantages

Advantages of vibration welding include relatively short cycle times, energy efficiency, capability of welding large parts, and insensitivity to surface preparation. Because of the smearing action due to friction, welds can be obtained on surfaces that have been vacuum metalized, painted, or contaminated. No additional materials are introduced as in the implant welding techniques or adhesive bonding, so the weld interface is composed of the same material as the welded parts. Heating is localized to a large extent, in contrast to hot tool welding, and material degradation resulting from overheating at the interface is much less likely to occur. The transmission properties of the materials have no effect on vibration welding, as they do in ultrasonic welding [1].

Parts can be welded regardless of how they were processed (injection molded, extruded, vacuum formed, etc.). Vibration welds produce high-strength, pressure-tight hermetic seals. In transparent materials, the weld is optically clear. Vibration welding should be used only on assemblies that do not have tight tolerances; although the melting points of plastics are predictable, the location at which the melt solidifies may vary slightly.

Due to the relatively high pressures used during vibration welding, the process has lower sensitivity to warped moldings compared to a process like hot plate welding. Any warpage at the joint line is flattened out by the pressure to ensure intimate contact of the weld faces.

A drawback of vibration welding is the initial high capital cost of the equipment and tooling compared to other processes such as hot plate or ultrasonic welding. However, this must be judged against the ability to weld larger parts at one go, with a faster processing cycle.

A problem that sometimes arises in vibration welding involves conversion of all the energy originating from the vibratory movement into heat energy in the joining zone. Kinetic energy is converted into heat energy both by internal friction and interfacial friction. The solid material friction in Phase I can cause high bending forces, so proper clamping must be used, and the thermoplastic must be rigid enough to avoid deformation. This is particularly important in cross-thickness welding, in which the direction of vibration is at right angles to the component wall. In practice, this is encountered in virtually every part, since all parts to be welded possess walls both in the direction of vibration and at right angles to it. If wall flexing occurs, then limited or zero frictional movement takes place between the parts to be joined, preventing weld formation around the entire component. This can be overcome by adding stiffening ribs to thin wall sections. In extreme cases, where there is excessive deflection in the parts, the plastic can start to melt directly at the clamping point, the point of maximum deflection; when this happens, a weld cannot be made [2].

When welding large parts that are difficult to lock into supporting fixtures either due to dimensional variations or due to lack of prominent features, relative motion can occur between the part and fixture, resulting in part slippage and energy loss. A satisfactory weld cannot always be obtained at high frequencies; in this case, use of lower frequencies is necessary to attain a high weld strength.

A feature of the process, which is a drawback for some end-use applications, is the generation of fine particulates or fluff at the joint line. The phenomenon is more pronounced with hard plastics and occurs during Phase I of the cycle as surface asperities become sheared away. This can be reduced by preheating the surfaces prior to welding (see Section 3.8.1).

Another disadvantage of vibration welding is sound generation, which is typically 90–95 dB. Sound enclosures are therefore required to reduce the noise to an acceptable level.

3.3 Applications

Vibration welding is commonly used on large parts, although smaller parts can be welded economically in multiple cavity tooling. Typical part sizes range from 3 × 3 inches (76.2 × 76.2 mm) to 24 × 60 inches (61.0 × 152.4 cm). The technique is used when strong, leak-proof pressure or vacuum joints are necessary.

Vibration welding is used extensively in the appliance industry for assembling such items as washer and dishwasher pumps, particulate-filled soap dispensers, and dishwasher spray arms. One large electrical appliance company converted a production line of glass-filled PP dishwasher pump housings from hot plate welding to vibration welding. The operation was faster, easier, more energy efficient, easier to maintain, and better control of strength and appearance was achieved [1, 3].

Automotive applications include headlight, taillight, and instrument panel assemblies (Fig. 3.3), where PC is welded to itself and to acrylic; acetal gasoline reservoirs, 30% glass-filled nylon brake fluid reservoirs, PP compartment access doors welded in two planes, dash-and-trim components, air-conditioning and heater ducts, vacuum reservoirs, fuel filler doors, and air flow sensors.

Figure 3.3. Automotive instrument clusters (Source: Branson Ultrasonics Corp.).

One of the first uses of vibration welding, in the late 1970s, was for assembling the first all-plastic automotive bumper that could withstand a five-mile per hour impact. Thermoplastic bumpers consist of a long curved U-section, commonly referred to as a front beam or facia, and a rear reinforcement, referred to as a back beam. Other techniques were evaluated for joining the two sections. Hot plate welding caused a time-aggravated embrittlement problem at the joint interface, while induction bonding was not cost-effective. Adhesive bonding was not used due to thermal cycling, low temperature impact limitations, and added weight. Holes required for mechanical fasteners would also raise local stress levels. Initial problems with vibration welding included the large part area (three times as large as any other previously welded part, with a four times larger joining area) and the necessity of applying clamping force in the horizontal rather than the traditional vertical direction, due to the attachment of the back beam on the inside of the U-channel legs. A large part vibration welder using an electromagnetic drive, with low (120 Hz) frequencies, and new fixturing for horizontal clamping forces was developed for this specific application.

Vibration welding is also often used in welding nylons in under-hood applications, which must withstand high temperatures. Lower costs and up to 50% savings in weight can be achieved. For example, nylon air intake manifolds were originally manufactured in one piece using the lost-core molding process, which, although useful for very complex manifold designs, was prohibitively expensive for the majority of applications. Linear vibration welding in this application revolutionized the manufacture of the intake manifold, by significantly reducing the overall capital cost. The manifold is made in two or three injection molded parts and linear vibration welding is used to assemble the final manifold (Fig. 3.4) [1].

In the aircraft industry, the method of joining PC air diffuser ducts was switched from adhesive bonding to vibration welding. Epoxy bonding required sandblast preparation, prebonding of parts, expensive fixturing devices, and a 24-hour cure time. With vibration welding, the labor cost was cut by 70%.

Other applications of vibration welding include joining two halves of pressure vessels, reservoirs, valves, electronic modules, and sealed containers in the medical, computer, recreation, and toy industries. It has also been used for welding chain-saw motor housings made of 30% glass-filled nylon, butane gas lighter tanks, batteries, and pneumatic logic boards. Vibration welding has also been proven for making high quality joints in polyethylene (PE) gas distribution pipes [1, 3, 4].

Figure 3.4. Vibration welded automotive air intake manifold (Source: TWI Ltd).

3.4 Materials

Almost any thermoplastic can be vibration welded: crystalline, amorphous, filled, foamed, and reinforced. The only polymers that can be difficult to weld are the fluoropolymers, due to their low coefficient of friction.

Properties of the materials to be welded affect the strength of the weld. Water absorption during storage increases the moisture content of some thermoplastics, which can sometimes lead to bubble formation in the joining area and decreased weld strength, although nylon and other hygroscopic resins can be welded without predrying [5].

In general, materials with high melting points will require higher energy input, and therefore longer welding times.

The welding behavior of materials that contain particulate or glass fillers (10%–30%) is similar to that of neat resins, but attainment of threshold penetration generally requires slightly increased welding cycle times; the time required is lower for glass than for particulate fillers. Increasing filler content reduces the weld strength relative to that of the neat resin by various amounts, depending on the amount and type of filler. For plastics reinforced with glass fibers and for liquid crystal polymers, a pronounced weak point develops in the welds compared to the neat material due to fiber reorientation along the direction of the weld [2, 6].

The thickness of parts to be welded affects welding behavior. Although the time required to reach the melting temperature (time elapsed during Phase I) is not dependent on part thickness, the lateral flow of the molten material during Phases II and III is affected, resulting in longer times to reach a steady-state flow (Phase III); in addition, the thickness of the weld is greater, resulting in increased solidification times. As a result, longer welding cycle times are required for parts with greater thickness. Welding times can be decreased by an increase in pressure. A pressure increase decreases the steady-state weld thickness and increases weld strength by decreasing the penetration necessary to attain the steady-state. At low pressures (0.52 MPa; 75 psi), high weld strengths of thick parts (12.3 mm; 0.48 inches) cannot always be achieved due to high required threshold penetrations. If penetration-based controls are used to terminate the weld cycle, threshold penetration must be adjusted to account for pressure and part thickness [7].

When welding dissimilar materials, properties of the two materials to be welded influence welding behavior and affect weld strength. Vibration welding can generally be used to join two materials differing in melt temperatures by up to 38°C (68°F). The extent of interdiffusion of the two materials that occurs in the molten state differs significantly for different materials, depending on diffusion coefficients, molecular weights, and cohesive energy densities, and affects the morphology of the weld. Shear mixing of the two molten polymers produces mechanical interlocking at the weld interface. Penetration versus time curves are similar to those of welding the same material, but different melting temperatures of the two polymers can result in a steady increase in weld strength with penetration, even after the threshold penetration has been reached. This results from an apparent steady state due to melting and flow of the lower melting polymer dominating the penetration in the early stages. As the temperature increases, the higher melting polymer melts at a faster rate, later reaching a steady state. Increasing penetration leads to greater strength; at high penetrations, weld strength equal to that of the weaker neat material can be obtained. Due to this behavior, penetration versus time curves alone cannot be used to determine optimum parameter conditions for welding dissimilar materials. Thermoplastics that are compatible include ABS to PC, ABS to acrylic, SAN (styrene acrylonitrile) to acrylic, SAN to polystyrene (PS), and PC to acrylic. There are no combinations where an amorphous material is compatible with a semicrystalline material [8].

3.5 Equipment

By necessity, vibration welding machines are large to ensure that there is sufficient mass to prevent the equipment from moving during the vibration cycle. Because of the noise generated by the welding process, sound insulation panels are built into the machine walls to protect the operator and those present nearby. These generally reduce the sound to values less than 85 dB. A typical linear vibration welding machine is shown in Fig. 3.5.

Equipment is classified as low frequency (120–135 Hz) or high frequency (180–260 Hz) and can be variable frequency or fixed frequency. Variable-frequency equipment is electrically driven, and adjustments can be made to tune the frequency to match the part and tooling mass. Fixed-frequency equipment is hydraulically driven, and a specific predetermined part/tooling mass is needed. Machines operating at high frequencies need less motion and less clearance between parts.

The three major components of a linear vibration welder are: a vibrator assembly suspended on springs, a lifting table, and tooling fixtures. A schematic of the components is shown in Fig. 3.6.

The vibrator assembly is a moving element with no bearing surfaces and is driven by either hydraulic pistons or electromagnets. Most commercial systems use the electromagnetic vibration system, which consists of two electromagnets, one at either end of the spring system, that are energized alternately. The springs resonate at

Figure 3.5. A typical linear vibration welding machine (Source: Branson Ultrasonics Corp.).

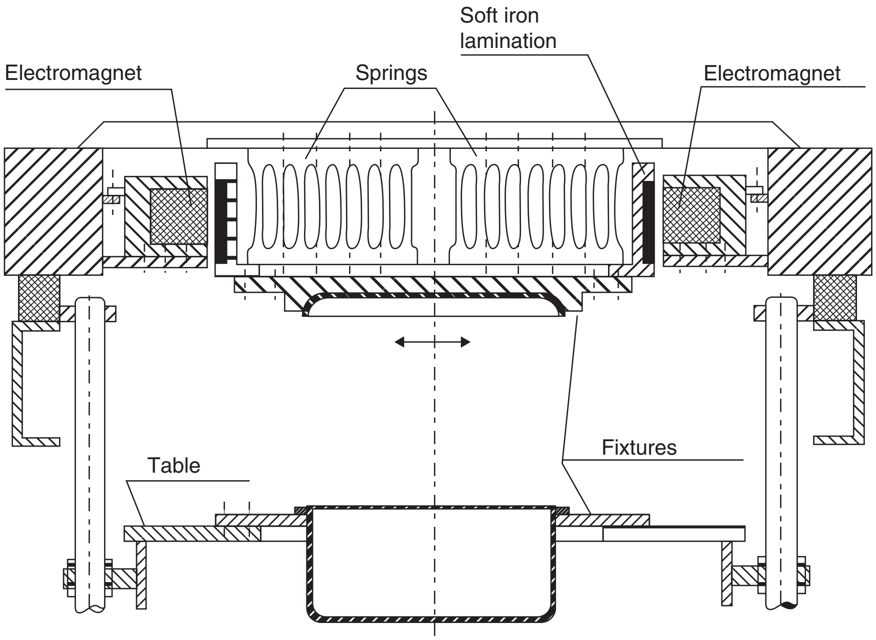

Figure 3.6. Schematic of the main parts of a vibration welding machine.

the frequency of the electromagnetic energy, support the vibrator assembly against the vertical welding pressure, and provide precise alignment between parts to be welded by returning the vibrator assembly to its home position at the end of the welding cycle. One of the parts to be welded is attached to the vibrator assembly in the upper tooling and the other part is clamped into the tooling fixed to the lifting table, the stationary element. For some applications, both parts to be welded are placed in the lower tooling. In this case, the parts should incorporate a molded pin or a similar feature, to aid alignment. The pin simply shears away when the weld cycle starts.

The lifting table brings the parts to be welded into contact, by raising the lower tooling and part to meet those attached to the vibration head. Guide rails ensure that horizontal positional accuracy is maintained. The table may be hydraulically, pneumatically, or electrically driven. The design of the lifting table provides sufficient mass and stability to counterbalance the vibration head. Recesses may be incorporated into the table to allow larger parts to be handled. After completion of the welding cycle, the table is lowered and the loading door opens to allow removal of the welded part.

Tooling used in vibration welding equipment is relatively simple, consisting of aluminum plates machined to conform to the contour of the parts at the joint. For complex part geometry, polyurethane nests can be used; these have the added benefit of reducing surface marking on the parts. The tooling must provide good support to ensure that an even pressure is applied to the weld interfaces during the welding cycle. It is essential that there is no relative movement between the parts and tooling fixtures during welding, otherwise the amplitude between the weld interfaces will be reduced. Simple clamping hooks and latches are used. Pneumatic clamps can be used with the lower tooling, whilst the upper tooling may incorporate vacuum cups to hold components in position prior to welding. Both upper and lower tooling will feature alignment ports into which dowel pins can be placed to assist with location accuracy during set up.

Since the vibrating head is a resonance system, the mass of the upper tooling is critical to achieving the correct amplitude and operating efficiency, that is, the frequency at which maximum amplitude occurs is governed by the tooling mass. Manufacturers provide guidance in terms of tool mass versus maximum amplitude, so that the tool design can be optimized. Modern microprocessor-controlled welding machines are able to “self-tune” to determine the resonance frequency after tool changes.

Tooling for larger parts may be split, often for manufacturing reasons, which allows easier handling for tool changes and adds an element of adjustment to compensate for tolerance variations in the parts to be welded. Figure 3.7 illustrates a set of upper and lower tooling.

A broad range of vibration welding equipment is available, with costs ranging from US $40,000 to

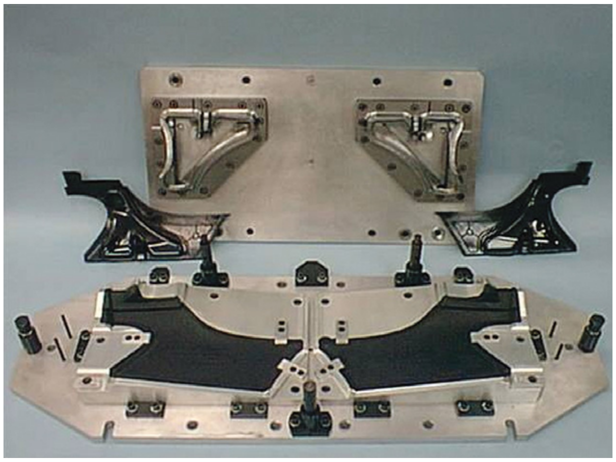

Figure 3.7. Upper and lower tooling for linear vibration welding (Source: Branson Ultrasonics Corp.).

$250,000, depending on size and options. Options available include closed-meltdown distance control, statistical process control, and robotic loading. Accurate table position monitoring and meltdown control during welding is accomplished using a linear displacement transducer (LDT), which eliminates the need for discrete table position limit switches and proximity sensors. Hydraulic, variable-speed lift and clamp systems ensure smooth and accurate positioning of the platen and make the use of multiple weld and hold pressures possible [3, 9–11].

3.6 Joint Design

In designing parts for vibration welding, there are two important considerations:

- Sufficient clearance must be provided in the joint to allow for vibratory motion between the parts.
- Parts must be sufficiently rigid to support the joint during welding.

In addition to these, strength requirements of the joint must be considered along with the visual appearance of the finished weld, that is, whether the flash on the outside is acceptable or not.

The simplest joint design is the butt joint, as illustrated in Fig. 3.8. Many applications for vibration welding tend to be enclosures, typically rectangular, so the vibrations will be both parallel and transverse to the wall orientation. To prevent the parts from snagging, the joint faces must never be completely out of contact, so the amplitude is normally restricted to 90% of the wall thickness.

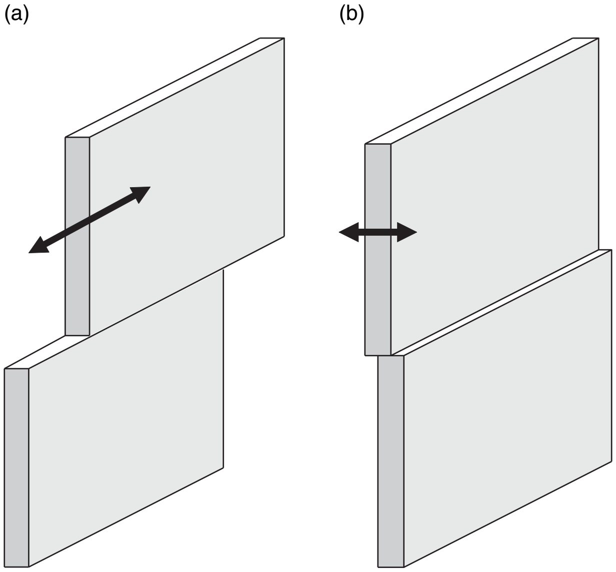

Figure 3.8. Simple butt joint for linear vibration welding: (a) motion parallel to wall, (b) motion transverse to wall (Source: TWI Ltd).

It is common practice to increase the wall thickness at the joint to two or three times the overall component wall, to provide rigidity that limits flexure, and to ensure that the weld is stronger than the parent material (Fig. 3.9). This design also facilitates gripping of the parts and the application of a uniform pressure close to the weld.

A U-flange (Fig. 3.10) may be necessary for thin or long unsupported walls, especially those where the vibration is transverse to the wall. It is designed to lock the component wall to the tooling fixture, thus preventing wall flexure. Walls as thin as 0.8 mm (0.03 inches) have been successfully welded with U-flanges.

If weld flash is unacceptable for aesthetic reasons, a flash trap can be designed into the joint. Functional and cosmetic designs are shown in Fig. 3.11. The trap should be volumetrically sized to the amount of material displaced during welding.

An alternative and more popular design is the tongue and groove design (Fig. 3.12). This design traps the flash within the groove inside the wall, rather than at the outside edge of the component. The tongue is typically one to three times the wall thickness of the component, depending on the strength requirements, and its height when welded, should approximately equal its width. Clearance for vibrational motion (±0.8 mm (±0.03 inches) for high frequency; 1.5 mm (0.06 inches) for low frequency) must allow for flash volume. An alternative is to use a basic tongue design with a skirted

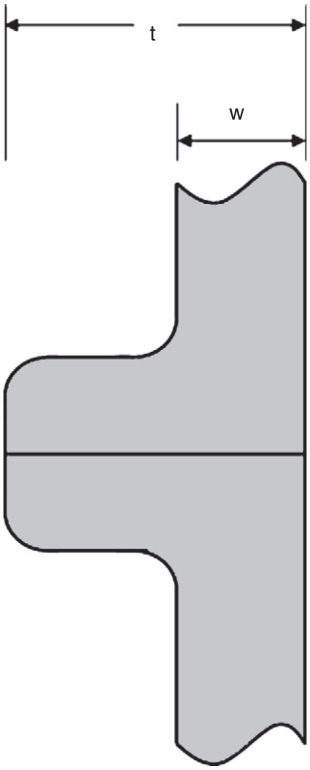

Figure 3.9. Increased thickness butt joint (Source: TWI Ltd).

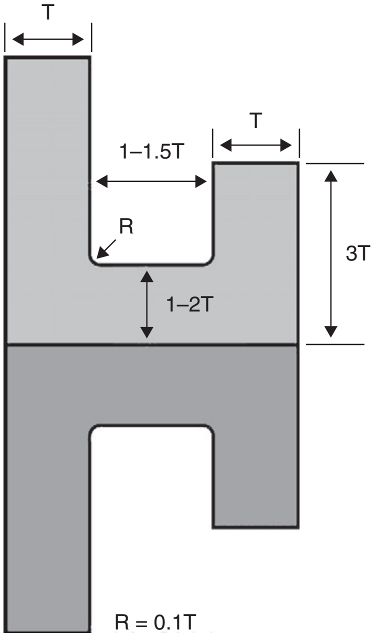

Figure 3.10. Butt joint with U-flange (Source: TWI Ltd).

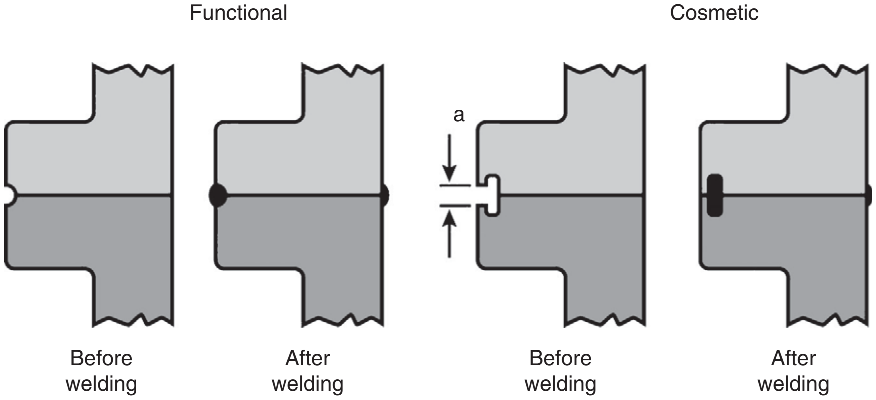

Figure 3.11. Flash trap designs for vibration welding (Source: TWI Ltd).

cover to hide flash, allowing 1.27 mm (0.05 inches) clearance for vibrational motion and tolerances.

3.7 Welding Parameters

Most industrial vibration welding machines operate at weld frequencies of 100–240 Hz, although machines with higher frequencies are also available. The amplitude of vibration, produced by exciting a tuned spring-mass system, is usually less than 5 mm (0.2 inches); weld time ranges from 1 to 10 seconds (typically 1–3 seconds), with solidification times, after vibratory motion has ceased, of usually 4–10 seconds. Total cycle times typically range from 6 to 15 seconds resulting in 4–10 cycles per minute.

To melt material at the joint interface, an amount of energy specific to the material must be introduced. This is proportional to the frictional speed between the two parts. In practice, determination of the maximum

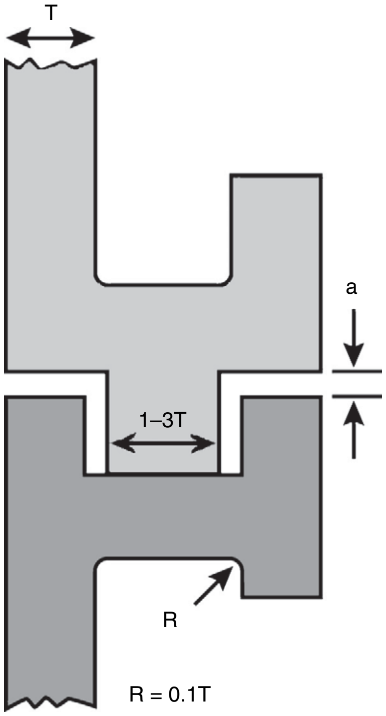

Figure 3.12. Tongue and groove joint (Source: TWI Ltd).

frictional speed between the mating surfaces, V, has proved useful. It is calculated from the peak-to-peak amplitude (a), in mm and the frequency (f) in Hz:

$$V = 2af$$

In general, V for welding should lie between 500 and 1000 mm/s (20–40 inches/s).

Lower weld amplitudes, (0.7–1.8 mm; 0.03–0.07 inches) are used with higher frequencies (240 Hz), and higher amplitudes (2–4 mm, 0.08–0.16 inches) are used with lower frequencies (100 Hz) to produce effective welds [1].

Generally, high frequencies are used when clearances between parts are restricted to less than 1.5 mm (0.06 inches) and/or when flash is undesirable, as in welding brake and steering fluid reservoirs. The greater amplitudes of low frequency welding are advantageous in welding parts with long, thin, unsupported side walls oriented perpendicular to the direction of vibration. These parts are susceptible to flexing, which inhibits welding; however, the greater displacement of low frequency welding in many cases negates the effects of flexing, so that a weld can be obtained.

Weld pressure varies widely (0.5–20 MPa; 72–2900 psi), although usually pressures at the lower end of this range are used (0.5–2.0 MPa; 72–290 psi). Higher pressures decrease the welding time; however, increasing the weld pressure can reduce the strength of the weld by forcing out all the molten plastic, resulting in a “cold” weld being formed. For example, in nylon, the weld strength is reduced by up to 40% when increasing the weld pressure from 1 to 20 MPa (145 to 2900 psi). Weld strength is generally not very sensitive to the frequency and amplitude of vibration, although some materials (i.e., polyetherimide) require high frequencies to attain high weld strengths [1].

Dual-stage welding pressure can have a positive effect on weld quality and can shorten the overall weld time. When welding with dual stage pressure, a higher welding pressure is used to start the interface material melting, and a lower pressure is used to complete the vibration cycle, resulting in optimum weld strength. The value of the low pressure in this modified process depends on the material [2, 12].

The most important determinant of weld strength is the weld penetration or displacement. Static strengths equal to that of the parent resin can be achieved when the penetration exceeds a critical threshold value, equal to the penetration at the beginning of the steady state Phase III; weld strengths decrease for penetrations below this value. Penetrations greater than the critical threshold do not affect the weld strength of unreinforced resins, chopped glass-filled resins, or structural foams, but can increase the weld strength of dissimilar materials. The threshold value increases with increasing thickness of the parts to be welded; a threshold of about 0.25 mm (0.01 inches) results in high-strength welds with material thicknesses of 6.3 mm (0.25 inches). As long as this threshold is reached, weld strengths are not very sensitive to welding frequency, amplitude, and pressure; however, at a constant threshold value, weld strengths can decrease with increasing weld pressure. Increasing the welding pressure or vibration amplitude increases the penetration rate and decreases the welding time by decreasing the time required to reach Phase III.

Vibration welding machines tend to have two control modes for regulating the welding cycle. These are the “weld-by-time” and the “weld-by-displacement” methods. When welding by time, the weld time is the length of time the plastic parts are rubbed together to create the heat. Ideally, the time should be terminated when the steady state phase of the weld cycle is reached. Higher melting point materials tend to require a longer weld time.

In the weld-by-displacement method, the parts are vibrated until a fixed material displacement is achieved, typically 1–2 mm (0.04–0.08 inches). The displacement value selected must be sufficient to ensure that steady-state melting occurs, and should also compensate for any possible deviation from flatness of the surfaces. If there are surfaces that are designed not to be welded, the displacement method can ensure that these surfaces do not make contact by the end of the weld cycle.

3.8 Process Variants

3.8.1 Linear Vibration Welding with IR Preheating

A feature associated with vibration welding is the formation of fine particulates or “fluff”. Studies have shown that these are generated during Phase I of the cycle, as surface asperities at the joint line become sheared away. In some applications, such as media-conveying parts and vessels for medical use, this soiling is unacceptable. Research has been carried out on the use of preheating methods to suppress the solid friction phase by ensuring that a melt film forms prior to the vibration welding cycle. Coil heaters and short-wave and fast medium-wave infrared (IR) emitters have been demonstrated to give a clear reduction in fine fluff formation (Fig. 3.13). IR emitters have the advantage that the preheat cycle can be kept relatively short (a few seconds), so the overall time-based advantage of vibration welding over hot plate welding is not significantly compromised [13].

3.8.2 Orbital Friction Welding

In orbital friction welding, one part is rubbed relative to another in an orbital motion, under axial pressure, as shown in Fig. 3.14. Unlike linear vibration welding, the relative motion of the two parts at the interface is the same at all points around the perimeter, and constantly changes from transverse motion to longitudinal motion.

Figure 3.15 illustrates the drive mechanism used to produce the orbital motion. The upper tooling plate is mounted on three central springs. At 120° spacing around the center column, three electromagnets are positioned. During operation, each electromagnet is energized in turn, pulling the tooling plate away from the center position. This continues throughout the weld cycle, producing an orbital motion. When the weld time is complete, the electrical energy to the magnets is switched off and the tooling returns to its original central position, ensuring good part alignment. An axial load is applied throughout the welding and cooling cycles.

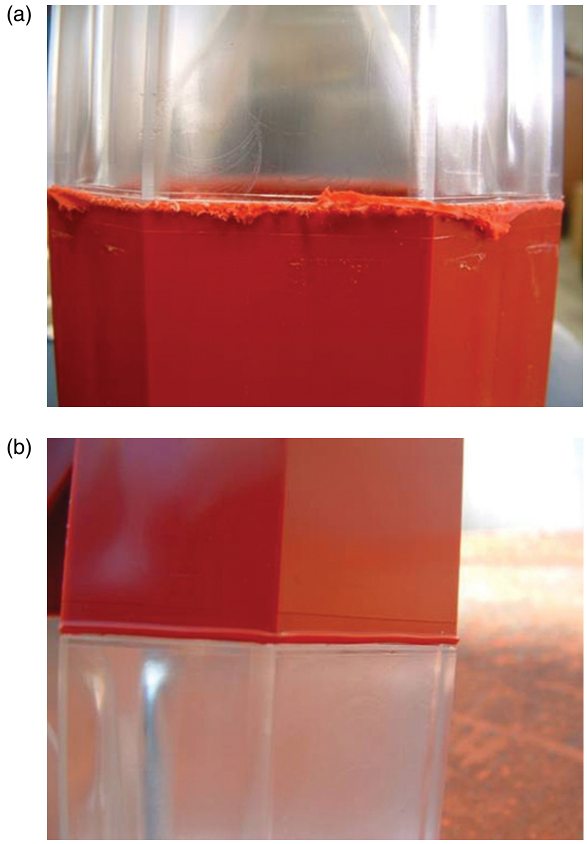

Figure 3.13. PC/ABS blend welded to clear polycarbonate: (a) without IR preheat, (b) with IR preheat (Source: Branson Ultrasonics Corp.).

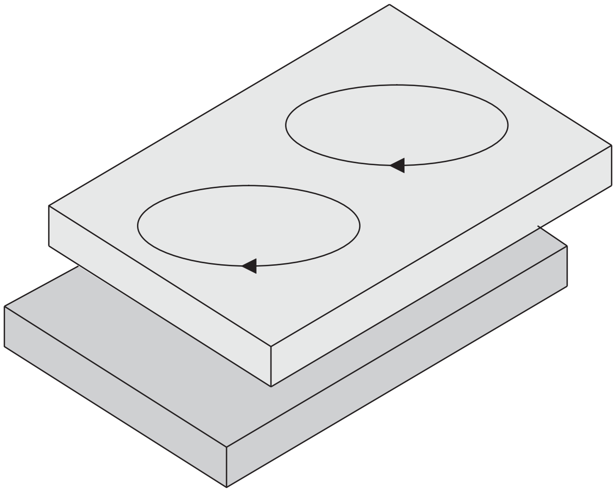

Figure 3.14. Depiction of orbital vibration welding (Source: TWI Ltd).

Because of the gentler motion created, and with amplitudes in the range 0.5–1.5 mm (0.02–0.06 inches), the process is better suited to components with relatively thin walls (<2 mm; <0.08 inches) or

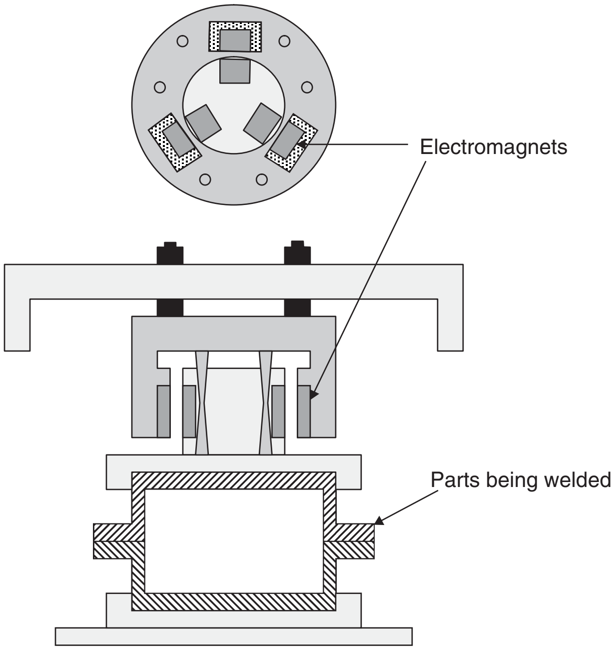

Figure 3.15. Schematic of system used to produce orbital motion (Source: TWI Ltd).

unsupported vertical walls. It is also better for components containing sensitive electrical parts. In addition, cycle times tend to be shorter than for linear vibration welding [14].

As with linear vibration welding machines, microprocessor-based orbital welders are available that include closed loop amplitude control, adjustable frequencies, touch-screen user interface, and process verification software for validating weld quality. The cost of a typical orbital vibration welder is about US $80,000 [10, 11].

3.8.3 Angular Friction Welding

Angular friction welding involves the rubbing together of components in an angular, reciprocating motion under axial force. The motion is indicated in Fig. 3.16. It is, in principle, similar to the linear friction welding process, except the motion is angular and is used for circular components. The arc of vibration is typically 2–5° with a frequency of 100 Hz. The process was developed for circular components where the final joint configuration is critical, but is not widely used in industrial applications these days, since the advent of spin welders with positional control.

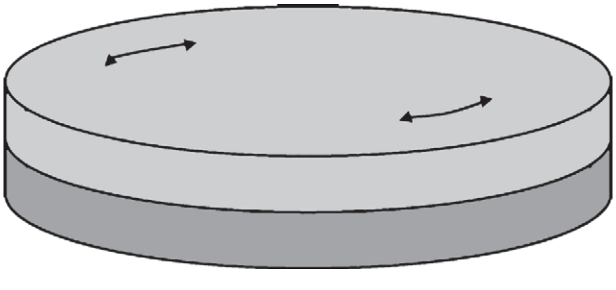

Figure 3.16. Motion produced by angular friction welding (Source: TWI Ltd).

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4 Spin Welding

4.1 Process Description

Spin welding, also known as rotational or rotary friction welding, is a process where thermoplastic parts with rotationally symmetrical joining surfaces are rubbed together under pressure in a unidirectional circular motion. Normally, one part is held stationary while the other is rotated. The heat that is generated during this process melts the plastic at the interface, forming a weld upon cooling. The process can be carried out on a dedicated spin welding machine or on a lathe or drill press.

The spin welding process can be divided into four main steps:

Step 1: Loading the Parts. This involves manually placing the parts into the machine. Often both parts are placed in a fixture mounted to the base of the welding machine (Fig. 4.1a). However, for larger parts, the upper part is often placed in the upper fixture, or drive head. The typical duration of Step 1 is 2–5 seconds.

Step 2: Press Actuation. This step is initiated by the operator, usually by the activation of two palm buttons. The drive head starts rotating and then descends to engage the upper part (Fig. 4.1b). Rotation speeds can range from 200 to 14,000 rpm, depending on the size of the parts to be welded, but are typically around 2000 rpm. The typical duration of Step 2 is 1–2 seconds.

Step 3: Welding. Once the drive head engages the upper part, it starts spinning and the relative motion between the parts generates heating and melting of the material at the interface. The welding process itself can be divided into four phases, as for vibration welding (Section 3.1). In Phase I, friction occurs between the two solid surfaces, generating heat and increasing the interface temperature to the glass transition temperature or melting point of the amorphous or semicrystalline polymer, respectively. In Phase II, the interface material begins to melt. As the melt thickness increases, part of the molten material is squeezed out of the joint as flash. In Phase III, a steady state is reached, where the rate of generation of molten material equals the rate at which material is displaced as flash. Once this stage is reached, the drive head is stopped from spinning, either by friction or by using a brake, depending on the system. The typical duration of Phases I–III is 0.5–2 seconds. In Phase IV, the drive head has stopped spinning and the parts are held together under a preset pressure to ensure intimate contact between the molten surfaces, and the joint is allowed to cool (Fig. 4.1c). The typical duration of Phase IV is 1–2 seconds.

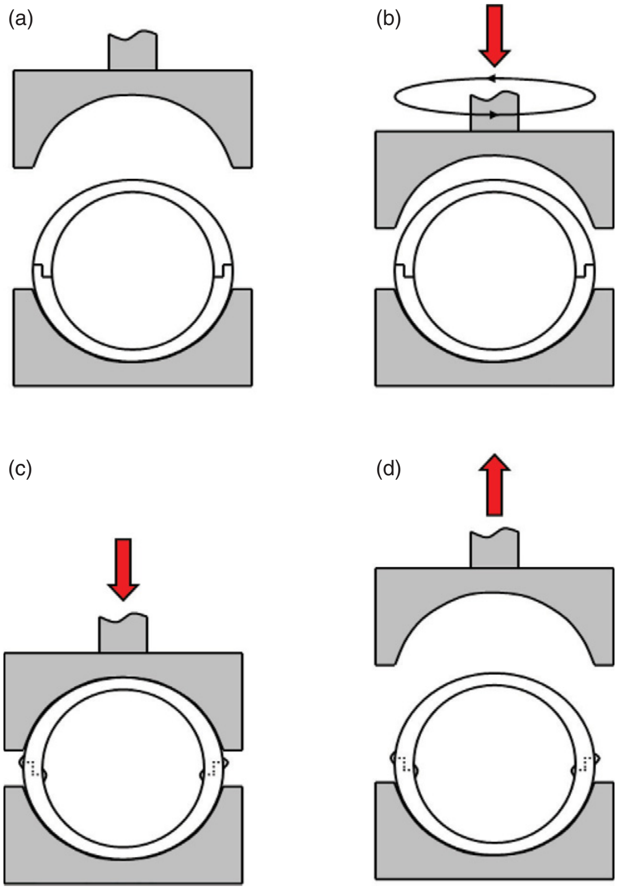


Figure 4.1. The spin welding process: (a) parts are loaded into the lower fixture; (b) drive head starts spinning and descends to engage with upper part; (c) welding takes place, rotation is stopped, and the assembly cools under pressure; (d) drive head lifts and welded part is removed (Source: TWI Ltd).

Step 4: Part Removal. Once the weld has solidified sufficiently, the drive head is lifted and the parts are removed (Fig. 4.1d). The typical duration of Step 4 is 2–5 seconds.

4.1.1 Spin Welding Modes

There are two main modes of spin welding: inertia and direct-drive.

In inertia welding, which is the simplest form of spin welding, the drive head is spun to a constant rotational speed using either pneumatic or electric motors coupled to a flywheel. This provides a constant kinetic energy stored in the rotating mass. The amount of kinetic energy can be varied by either changing the rotational speed or the mass of the drive head. When the set rotational speed is reached, the drive motor is disengaged and the press is actuated. The drive head rotates freely until all the kinetic energy stored is transferred to the joint. The pressure should be adjusted so that this takes around a second; if it takes any longer, the melt at the interface will be sheared as it starts to solidify, reducing the weld strength. Inertia spin welding can be carried out on simple equipment. However, with this technique it is not possible to control the final angular position between the two parts at the end of the cycle.

In direct-drive spin welding, the rotational speed remains constant throughout the welding stage. This can be accomplished by using either a lathe or a drilling machine as well as dedicated spin welding equipment. For applications where specific alignment between the two parts is critical, spin welding machines are available that use a servo- or step-motor that can be programmed to stop rotating almost instantaneously at a preselected angle.

4.2 Advantages and Disadvantages

Spin welding is a simple and highly energy efficient process; there is little excess heat generated, which means that cooling times are short. This makes the process well-suited to automated assembly line applications. Strong, hermetic joints can be produced, which are frequently stronger than the parent parts. No foreign materials are introduced into the weld and no environmental considerations are necessary, as in solvent welding or adhesive bonding.

Theoretically there is no limit to the maximum size of the parts that can be spin welded and parts over 1m diameter have been welded. However, most applications are 300 mm (12 inches) or less. For joining long, tall parts, spin welding is better than far-field ultrasonic welding, especially if the parts are contoured or have openings, or if the materials are semicrystalline.

Inertia spin welders and their tooling are relatively inexpensive, although direct-drive models, which can achieve orientation tolerances in the range ±0.5–2.0°, can cost between 50% and 300% more.

The main disadvantage of spin welding is that the technique is limited to circular fitments.

4.3 Applications

The first reported application for spin welding was in the manufacture of fluid-filled compasses, where welding was carried out beneath the surface of the liquid. The process can therefore be used for sealing a liquid in a container. Other applications include fuel filters, check valves, truck lights, aerosol cylinders, and floats. Spin welding is also used for assembling structural components, connecting ventilation pipes to blow-molded fuel tanks, and welding tops and bottoms on containers. In addition, it has been used for the joining and repair of PE pipes [1–3].

Examples of spin welded items are shown in Fig. 4.2.

4.4 Materials

Almost all thermoplastics can be joined using spin welding. Table 4.1 gives the weldability of most common thermoplastics.

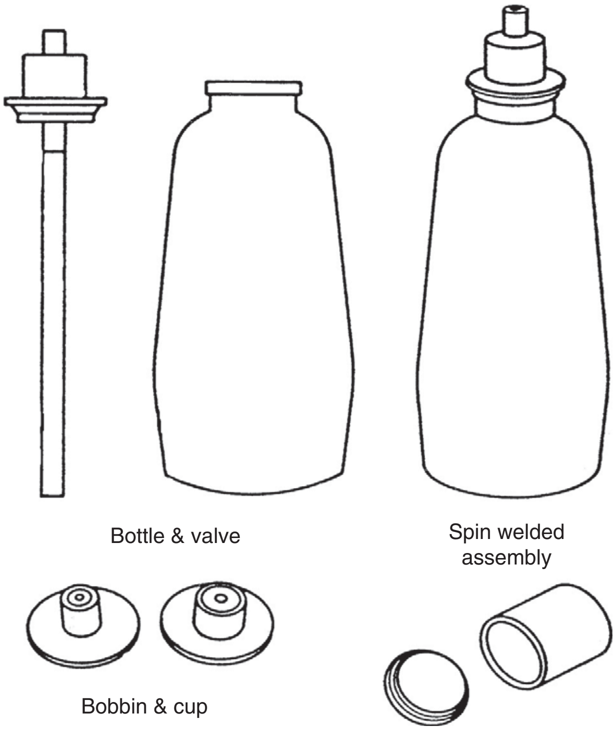


Figure 4.2. Bottles, bobbins, and cups joined using spin welding.

Table 4.1. Spin Welding Characteristics of Various Thermoplastics [4]

Material	Weldability
ABS	Good to excellent
ABS/PC alloy	Good
Acetal	Fair to good
Acrylic	Good
ASA	Good
Cellulosics	Good
Liquid crystal polymers	Fair to good
Nylon	Good
PAI	Fair to good
PBT	Good
PC	Good to excellent
PC/PBT alloy	Good
PE	Good
PEEK	Fair
PEI	Good
PES	Good to excellent
PET	Fair to good
PFA	Poor
Polymethylpentene	Good
Polyurethane	Poor to fair
PP	Good to excellent
PPS	Good
PS	Good to excellent
PSO	Good
PVC (rigid)	Good
PVDF	Good
SAN	Good to excellent
Styrene-butadiene copolymer	Good to excellent

As with any friction welding process, materials with high melting points will require higher energy input, and therefore longer welding times.

Additives such as silicones and other lubricants will reduce the friction coefficient of the material, which will make them more difficult to weld. Fillers may also have an effect on weld strength; for example, with a high percentage (>30%) of filler, the amount of polymer at the interface available for welding is reduced, and a reduction in strength can occur. Also, since fiber reinforcement will not ‘cross’ the joint line, the maximum weld strength that can be achieved is that of the unreinforced resin. Therefore, this must be compensated for by increasing the weld area.

4.5 Equipment

Spin welding machines can vary significantly in their design and complexity, ranging from lathes and modified drills to direct-drive, computer-controlled models. In most inertia spin welders a pneumatic motor supplies the spinning motion. A control valve is used to regulate the air flow to the motor, which drives the flywheel, connected to the drive head. A typical inertia spin welding machine is shown in Fig. 4.3. In direct-drive welding machines the pneumatic motor, control valve and flywheel are replaced by an electric drive motor.

In both systems, the vertical travel and welding pressure are normally controlled by an air cylinder, and there is usually a pressure regulator, which controls the maximum force applied during welding. Often the press will incorporate an encoder to measure the weld displacement.

Figure 4.3. Typical inertia spin welding machine (Source: Forward Technology).

4.5.1 Lower Tooling

The design of the tooling is an important aspect of spin welding. The parts being welded must be adequately supported to prevent them from flexing or moving during the welding operation. Therefore, the lower tooling (nest) should support the component walls as close to the joint line as possible (Fig. 4.4).

The lower tooling can be manufactured from either aluminum or metalized epoxy molding compound. When manufacturing the tooling from aluminum, it is recommended that a matched copy of the component be made. This can be achieved by CNC machining or copy milling from a cast female model of the actual component. This ensures that there is intimate contact between the part and tool.

4.5.2 Upper Tooling

The upper tooling should be manufactured from metal, since epoxy resins may not evenly spread throughout the mold, which would produce an unbalanced tool.

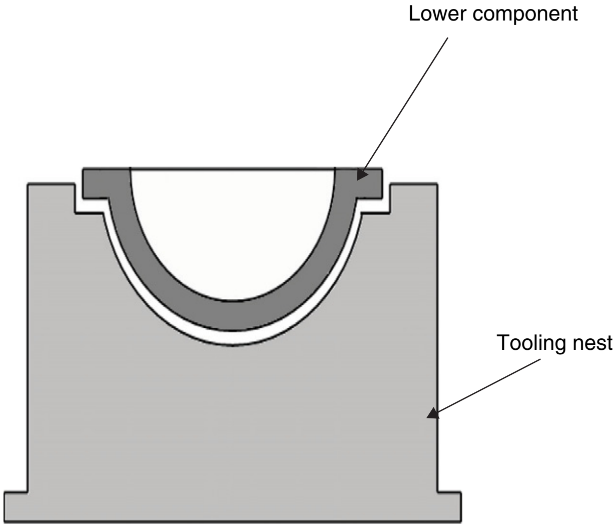


Figure 4.4. Lower component support (Source: TWI Ltd).

Where the upper part is fixed into the machine before welding, the upper tooling should be made so that the part can be press-fitted into position. This will avoid the component dropping out during welding. Drive pins can also be added to the tooling to locate the component and prevent slippage.

Where both parts are placed into the lower tooling before welding, the upper tooling has a surface preparation such as serrations or a grit-blasted finish. These profiles grip the component as the rotating surface and stationary component meet. Note that some part marking can occur when using this process. However, if the teeth are designed correctly and the actuator moves fast enough, these markings can be minimized.

To prevent the component flying out of the tooling when rotating, a raised guard area should be provided immediately around the weld area. This can be incorporated into either the upper or lower tooling (Fig. 4.5).

4.6 Joint Design

Joint design is a critical factor when designing thermoplastic components for spin welding. Care should be taken to ensure that the joint achieves the desired result; that is, it produces an aesthetically pleasing appearance and/or gives the desired weld strength.

When designing a component for spin welding, the simplest joint design is the butt joint. Figure 4.6 shows a simple butt joint before and after welding. This joint design would only be used where weld flash is acceptable in the final component.

In some cases the wall thickness of the component is thickened in the weld area to give greater joint strength and part rigidity (Fig. 4.7).

To exclude weld flash from areas that are visible, flash traps can be added. Figure 4.8 shows two simple butt joint designs where the location of the flash is controlled. The left-hand-side example shows how the flash can be controlled so that it is contained inside the

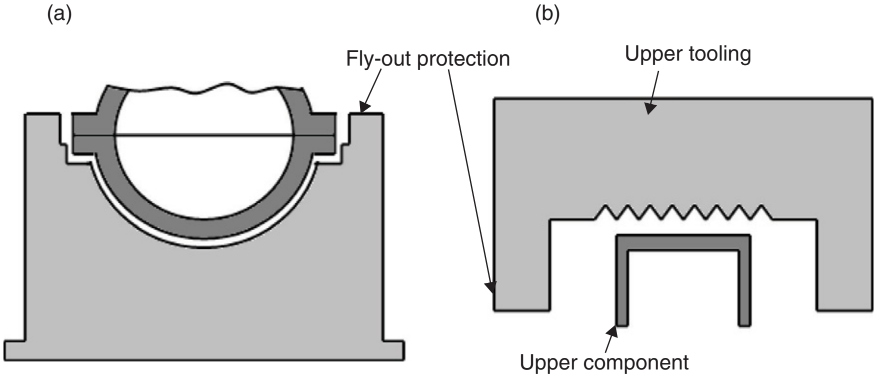
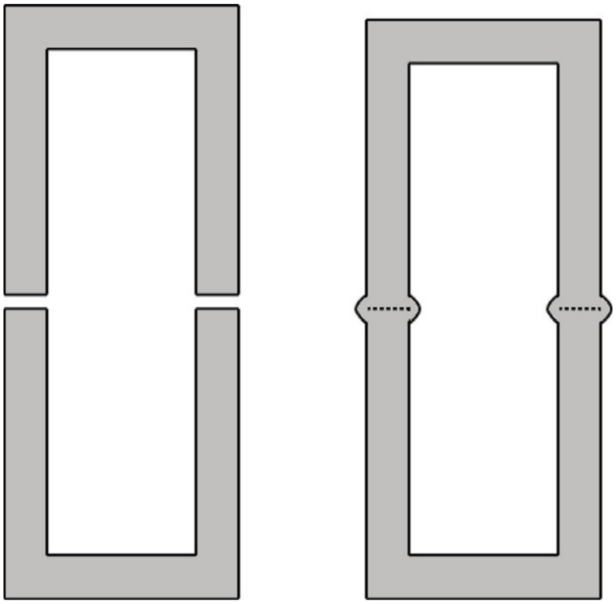


Figure 4.5. Component fly-out guarding: (a) lower tooling, (b) upper tooling (Source: TWI Ltd).



Before welding After welding

Figure 4.6. Simple butt joint for spin welding (Source: TWI Ltd).

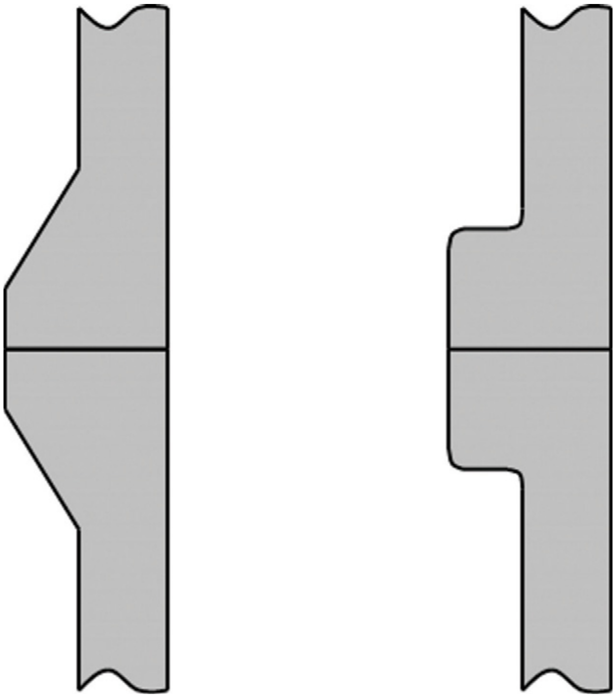
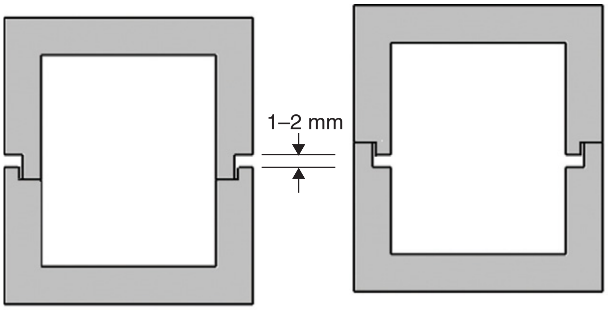
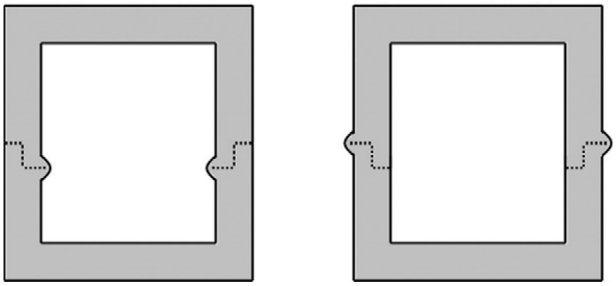


Figure 4.7. Simple butt joints with thicker wall at weld area (Source: TWI Ltd).



Before welding



After welding

Figure 4.8. External (left) and internal (right) flash trap designs for simple butt welded joint (Source: TWI Ltd).

welded component. The inside step on the upper component is higher than the outside step on the lower component. Therefore when melting occurs, the inside step will melt first and material will be displaced to the inside of the component. When sufficient material has melted, the outside steps of the upper and lower part will touch, but will not be joined.

It is important to note that in this design, the welded area is only half the wall thickness of the overall component. If the weld strength was 100% of the parent material strength, then the joint strength would only be 50% of the parent material strength.

In the designs shown in Fig. 4.9, the use of angled slots and conical faces achieves self-centering of the parts during welding as well as prewelding part location. These particular joint designs also increase the surface area of the weld at the interface, reducing the need for a thicker wall section in this area. These designs do not include flash traps.

Figure 4.10 shows several tongue-and-groove joint designs, which include part alignment, self-centering, flash traps and extended weld areas. The simplest form is shown in Fig 4.10a, which does not include a flash trap but has a small recess at the edge to which the flash is directed. In this design, the flash remains flush with the outside surface of the component and is visible after welding. The gap between the parts before welding (a) should be approximately 0.1 × the wall thickness of the component. To prevent self-locking during welding, the angle (b) should not be less than 30°. Finally, the cross-sectional length of the weld surface (c + d) should be at least 2.5 × the component wall thickness to ensure adequate joint strength is achieved. Stiffening ribs can be added to the wall of the component for extra rigidity.

The joint design in Fig. 4.10b has a flash trap molded onto both halves of the component. In this design, the joint line is visible when the component is welded but the flash is not. The size of the flash trap must be sufficient to contain the plastic material that flows from the weld interface. In practice it is best to add slightly more space than necessary to allow for possible overwelding.

Figure 4.10c shows a skirt design, where the flash is contained within a groove and the joint line is also hidden underneath the skirt.

The most suitable joint design must be selected based upon the desired end result (Table 4.2).

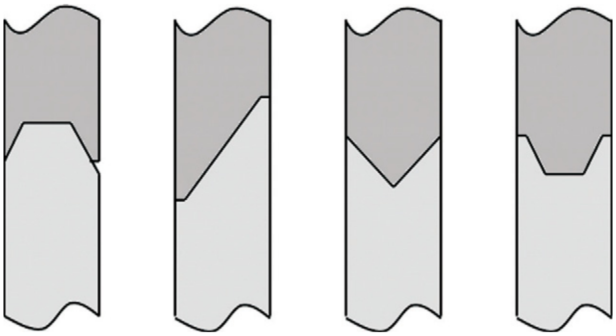


Figure 4.9. Simple butt joint designs for spin welding that include component self-centering (Source: TWI Ltd).

4.7 Welding Parameters

For all welding processes there are three main parameters; heat, time, and pressure. The way in which each parameter is controlled depends upon the welding process. For example, in both direct drive and inertia spin welding the heat is generated by friction. However, direct drive uses time to produce sufficient heat, and inertia uses stored energy in the rotating flywheel to produce sufficient heat.

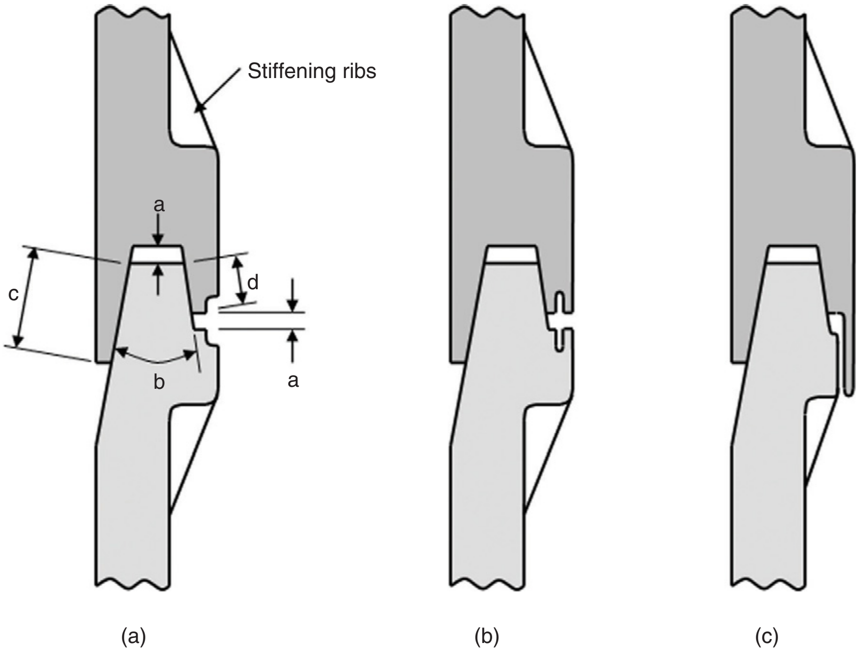
1. *Weld Force/Pressure*. In spin welding, pressure is only applied to the joint after the rotating head contacts the components. Typically, the weld pressure for thermoplastics is between 0.5 MPa (72.5 psi) and 2 MPa (290 psi). The required welding force to be applied to the parts to give the weld pressure is calculated by:

$$\text{Weld force (N)} = \text{Weld pressure (MPa)} \times \text{Weld area (mm}^2\text{)}.$$

2. *Cooling Time*. The cooling time is the length of time during which the parts remain under pressure after the rotation has stopped. This should be sufficient to allow the weld material to cool and solidify, and is generally determined by experimentation.

4.7.1 Inertia Spin Welding

1. *Rotation Speed and Mass*. The energy for welding is initially stored in the rotating flywheel before the drive head is brought into contact with the plastic part.



(a) (b) (c)

Figure 4.10. Tongue-and-groove joint designs for spin welding: (a) basic joint, (b) joint with flash trap, (c) joint with skirt (Source: TWI Ltd).

Table 4.2. Joint Design Selection Criteria

Joint Strength	**Appearance**		
	Not critical ←		**→ Critical**
Not critical ↑	Simple butt joint without flash trap (Fig. 4.6)	Simple butt joint with internal or external flash trap (Fig. 4.8)	Simple butt joint with internal and external flash traps
	Simple butt joint with thicker wall in weld area (Fig. 4.7)	Simple butt joint with thicker wall in weld area and internal or external flash trap	Simple butt joint with thicker wall in weld area and both internal and external flash traps
Critical ↓	Angled or tongue-and-groove joint (Fig. 4.9 or Fig. 4.10a)	Tongue-and-groove joint with flash trap molded in both components (Fig. 4.10b)	Tongue-and-groove joint with flash trap hidden below joint line (Fig. 4.10c)

The amount of energy is varied by changing the rotation speed or the mass of the drive head. The rotation speed is typically between 2500 and 4000 rpm and the head mass is typically 1–4 kg (2.2–8.8 lb).

2. *Run-up Time*. The run-up time is the time for the drive head to reach its maximum rotation speed. The energy input to the joint can therefore be varied without changing the drive head mass by bringing the head onto the components part way through the run-up time.

4.7.2 Direct-drive Spin Welding

1. *Rotation Speed*. In direct-drive spin welding, one component is rotated at a fixed speed against the stationary component. The required rotation speed depends on the material and application. Each material will have an optimal interfacial linear speed to generate the friction and heat. For example, if the required linear speed at the joint is 2 m/s, for a component with a diameter of 40 mm, the rotation speed must be:

$$\frac{60\ \text{s} \times 2\ \text{m/s}}{0.04\ \text{m} \times \pi} = 955\ \text{rpm}$$

For components with larger diameter, the rotation speed must be reduced in order to maintain the optimal linear speed at the joint. Typically, the linear speed at the joint will be between 0.2 and 2 m/s (0.6–6 ft/s). The optimum value is determined by experimentation.

2. *Welding by Time*. The weld time is the time that the rotation between the components is maintained. The longer the weld time, the greater the heat generated at the interface. As with vibration welding, there is a steady state phase, where the rate of material displacement increases linearly with time. When this state is achieved, no further benefit is gained from continuation of the head rotation. The weld time can range from 2 to 10 seconds depending on the material and joint diameter. Optimum weld times are determined experimentally.

3. *Welding by Displacement*. If a predetermined displacement of material is required, for example when two mating surfaces must finish flush, then the welding process can be controlled by displacement, that is, when the required displacement is achieved, the rotating head is stopped. As with welding by time, optimal quality welds will be achieved as long as the steady state phase has been reached. This can be determined by placing a displacement transducer between the base of the machine and drive head and monitoring the displacement with time.

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5 Radio Frequency Welding

5.1 Process Description

Radio frequency (RF) welding, also called high frequency welding, HF welding or dielectric welding, uses high frequency (normally 27.12 MHz) electromagnetic energy to generate heat in materials by virtue of their electrical properties; the material to be welded must be able to convert the alternating electric field into heat. Polar molecules in an electric field tend to orient in the field direction so that the positive (or negative) end of the dipole aligns to the negative (or positive) charges in the electric field. This process is called dipole polarization. Nonpolar molecules in an electric field displace electron clouds to align with the field (electronic polarization), so that centers of positive and negative charges no longer coincide. Electronic polarization is instantaneous and does not result in heat generation. Dipolar polarization, however, is not instantaneous at the high frequencies used in RF welding; as the dipoles try to align with the rapidly alternating electric field, orientation becomes out-of-phase. The imperfect alignment causes internal molecular friction and results in the generation of heat.

The delay between changes in electric field direction and changes in dipolar polarization is shown in Fig. 5.1. An oscillating electric field E generates an oscillating current I within the polar material. At high frequencies, the two curves are out of phase by the phase angle θ; the loss angle is defined as $90 - \theta$ or δ. The amount of energy absorbed per cycle from the electric field is represented by the power factor and the dissipation factor; the power factor is defined as $\cos \theta$, and the dissipation factor or loss tangent is $\tan \delta$, a ratio of current dissipated into heat to current transmitted. The amount of dipole polarization is dependent on frequency and temperature. At low frequencies, the power lost by the electric field is low due to dipole alignment with the electric field. At high frequencies, field reversal is so rapid that dipole alignment becomes out of phase, and power losses increase. Eventually, a maximum in power loss is reached, so that further frequency increases result in decreased power loss. Dipole polarization is low at low temperatures but increases with increasing temperature [1].

Typically, an RF welding machine has two platens—an upper, moveable one and a lower, fixed one, also called a bed. The upper platen is connected to the RF generator, whilst the lower platen is connected to electrical earth. Tooling, known as the electrode or welding rule, is attached to the upper or lower platen and defines the shape and dimensions of the weld.

The parts to be welded are placed between the platens and a press then lowers the upper platen so that a preset amount of pressure is applied to the joint area. Once the parts are clamped, the RF energy is applied for a preset time, called the heating time. Once the heating time has elapsed, the electrodes continue to clamp the parts until the weld solidifies. This is called the hold or cooling time. The press then opens and releases the welded assembly.

RF welding is normally only used for joining films and thin sheets. This is because a sufficiently strong electric field to produce material melting can only be achieved when the gap between the electrode and the opposing platen is less than around 1.5 mm (0.06 inches).

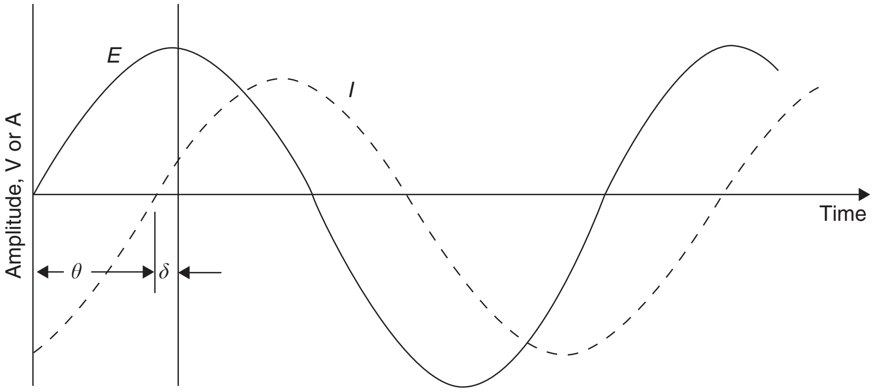

Figure 5.1. Electrical representation of dipole polarization resulting in heat generation due to imperfect alignment.

Table 5.1. Advantages/Disadvantages of RF Welding

Advantages	Disadvantages
Fast cycle times	Limited joint thickness
Economical	Material limitations
Ideally suited to flat and thin components	Limited joint complexity
Capable of welding multiple layers simultaneously	Component size limitations
Easily automated	
Repeatable	
Good weld appearance (minimal flash)	
Tool runs cold	

5.2 Advantages and Disadvantages

RF welding uses simple, compact equipment and requires only electricity and compressed air. In addition, no solvents or adhesives are introduced into the joint, minimizing sources of contamination and assisting recyclability of the welded parts. Also, cycle times are fairly short (up to 20 parts per minute).

In addition, RF welders can also be used to produce more than just welds. Electrodes can be fabricated to produce what is commonly called a 'tear/seal', which allows the sealed part to be pulled away from the surrounding material without the need for a secondary cutting operation. A hinge or folds can also be introduced in a product without material distortion by producing score marks.

The major disadvantage of RF welding is that it is only suitable for materials containing polar groups in the molecular structure. Nonpolar plastics can be welded but this requires a conductive-composite implant at the joint interface [2].

A summary of the advantages and disadvantages of RF welding is shown in Table 5.1.

5.3 Applications

RF welding is commonly used in sealing thin sheets and films of plasticized PVC for stationery products, such as loose-leaf binders, checkbook covers, credit-card holders, and book covers. Another large market is in inflatable products, such as beach balls, airbeds, life jackets, and inflatable dinghies.

Other applications include medical items, such as colostomy and blood bags (Figs. 5.2 and 5.3), disposable clothing, and inflatables, such as blood pressure cuffs, inflatable beds, and cushions (Fig. 5.4). Clamshell-style blister packs and other types of packaging also utilize RF welding [3, 4].

Figure 5.2. RF welded blood bag (Source: TWI Ltd).

Figure 5.3. RF welded dialysis fluid warmer bags (Source: Dielectrics Inc.).

Figure 5.4. RF welded inflatable wheelchair cushion (Source: Dielectrics Inc.).

5.4 Materials

To ensure weldability with the RF process, the materials must have the following properties:

- High dielectric loss.
- High dielectric constant.
- High dielectric breakdown.

Such materials include PVC, thermoplastic polyurethanes, nylons, PET, cellulose acetate, EVA, PVDC, and some ABS resins.

Materials generally considered not compatible with this method of welding include PTFE, PC, acetal, PS, and rigid materials with high melt temperatures. Standard grades of PP and PE are also not possible to join with this method. However, special grades are available that are RF weldable.

5.5 Equipment

RF welding machines typically consist of six major components: an RF generator, a control unit, a press unit, an RF enclosure, a workpiece handling mechanism, and tooling.

5.5.1 RF Power Generator

Generators commonly provide powers ranging from 1 to 25 kW. Power requirements are determined by the weld area and the thickness and type of material being welded. The power supply in the generator converts incoming alternating current to high-voltage direct current using solid state rectifiers; an oscillator then converts this to high-voltage alternating current. The power level is displayed on an output power meter. The operator can therefore check if a satisfactory weld is made by monitoring the output power during the welding cycle. Safety and overload protection devices automatically shut down the system if a large amount of energy becomes concentrated in a small working area [3, 4].

5.5.2 Control Unit

The control system ensures that the machine can be started, stopped, and operated efficiently. Machine control systems typically range from simple mechanical controls to complex electrical systems on large automated machines, which typically contain software controlled devices, such as microprocessors and programmable logical controllers (PLCs). These systems enable operating parameters to be accurately implemented with excellent repeatability.

To compensate for material thickness variations, current detectors monitor the current during the welding cycle; when the optimum current is reached rapidly, the current detector ends the cycle, preventing overwelding or burning. If the optimum current is not reached, the detector will extend the welding cycle and prevent an underweld occurring.

5.5.3 Press

The press or actuator provides pressure during the welding process and usually contains one fixed and one moveable platen. Pneumatic presses are most common, although hydraulic presses up to 50 tons are necessary for larger equipment or welding applications. Presses have adjustable guide rods with bushings for accurate movement and are normally constructed of heavy-duty tubular steel for stabilization and ruggedness.

There are two main types of press: a “C” type and a bridge press. The “C” type press resembles the letter C in side view. Since the main body of the press is at the rear of the machine, the working area is unobstructed (Fig. 5.5). In the bridge press, the upper platen is supported from both sides of the working area. This type of press is more symmetrical but access to the working area is limited.

5.5.4 RF Enclosure

A cage or enclosure is mounted around the fixtures and electrodes to protect the operator from the high

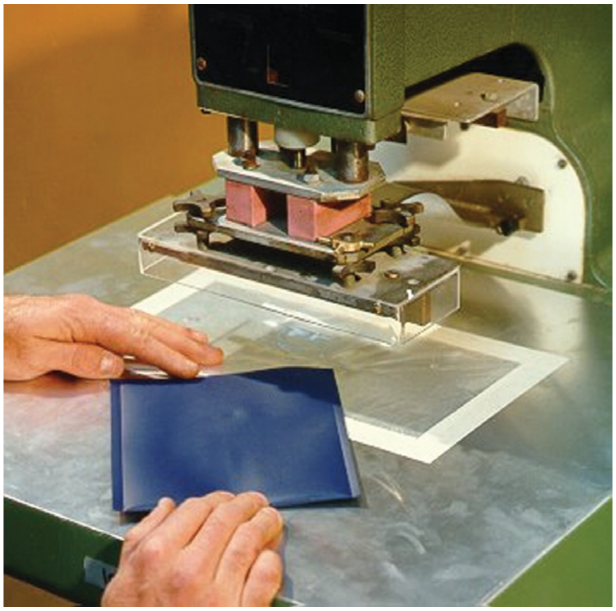

Figure 5.5. "C" type RF welding machine (Source: TWI Ltd).

voltages emitted from the electrodes and to reduce RF radiation emissions in order to comply with Federal Communication Commission (FCC) and electromagnetic compatibility (EMC) regulations.

The enclosure is often fabricated from a metallic mesh, which allows proper shielding of the RF energy without obscuring the view of the operator (Fig. 5.6).

5.5.5 Handling Mechanism

The handling mechanism transfers the parts to be welded to the press, locates them in the correct position under the electrode, and removes them after welding. There are four main types of handling mechanism: manual, rotary, linear, and rail.

In manual machines, such as those operated using a foot pedal, the parts to be welded are fed into the machine, positioned for welding and removed after welding by hand.

In rotary machines (Fig. 5.7), a circular table containing a number of workstations is used. The parts are manually assembled in the workstations by one or more operators and the table rotates to bring the parts to the press. After the welding operation, the table rotates again and the welded parts are removed manually while the next parts are welded.

In linear machines, the parts to be welded are fed to the press using a conveyor belt. The belt stops at the

Figure 5.6. RF welding machine with metallic mesh RF enclosure (Source: Sealectric Corp.).

Figure 5.7. Rotary RF welding machine (Source: Cosmos Kabar).

correct position for welding and then moves on to remove the parts after welding.

Rail systems are used where the parts are too big to be accommodated in a fixed machine (e.g., swimming pool liners and tarpaulins). In these systems, the parts to be welded are held fixed while the welding press is moved on a rail system to carry out repeated welds.

5.5.6 Tooling

The tooling (or electrode) is the part of the machine that is pressed onto the parts to produce the weld. It is made of brass, copper or bronze sheet metal, typically 2–4 mm (0.08–0.16 inches) thick, and is mounted on an aluminum tool plate, which is normally bolted to the top platen. The electrode is machined into the particular shape needed for the application. In applications where aesthetics is considered an important factor and the geometry of the part does not allow for a flat lower fixture, the lower fixture may also be profiled. This type of welding setup defines the electric field better and results in a more defined weld area.

5.5.7 Barrier Materials

Materials with high dielectric properties (referred to as barrier materials or buffers), such as phenolic laminates, electronic fish paper or polyester film are often placed between the parts to be welded and the lower platen. They serve two purposes: firstly, they provide a thermal barrier, reducing the heat loss to the lower platen, and secondly they prevent the electrode touching the bottom platen and causing an arc during cut/seal operations.

5.6 Joint Design

Various types of joint can be produced by RF welding depending on the shape of the electrode, or welding rule, including plain seam welding, tear/seal welding, and combined plain and tear/seal welding.

In plain seam welding (Fig. 5.8) a flat-ended welding rule is used. This type of weld is used to produce folds and can also be used to produce patterned welds, by machining the face of the rule.

In tear/seal welding (Fig. 5.9) a knife-edged welding rule is used to produce a very thin welded seam that can be torn after welding to enable the welded part to be separated from the surrounding material. For this application, a barrier material must be placed underneath the parts to be welded to prevent the welding rule from touching the lower platen, which would generate an arc and also blunt the rule.

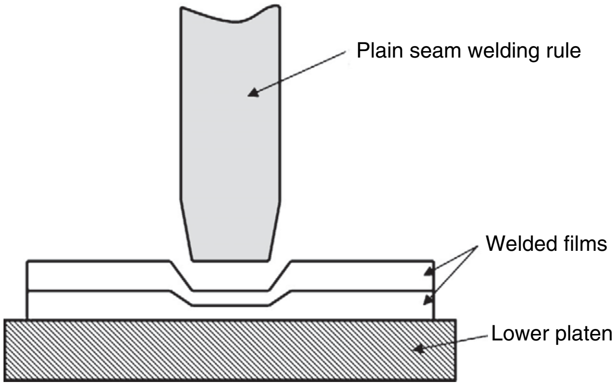

Figure 5.8. Plain seam welding (Source: TWI Ltd).

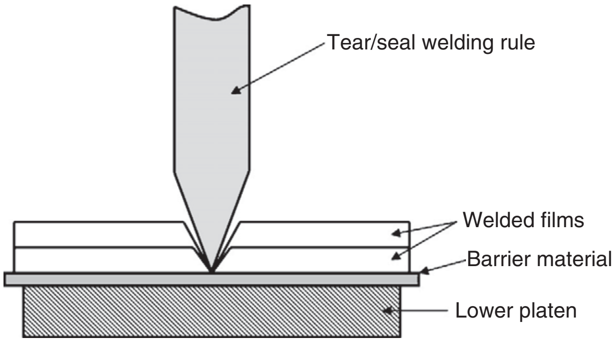

Figure 5.9. Tear/seal welding (Source: TWI Ltd).

One of the problems with a tear/seal weld is that the integrity of the joint is not high due to the narrow weld width. Therefore, to produce a high strength weld that can be easily separated without a secondary cutting operation, electrodes can be designed to produce a tear seal next to the welded edge, by putting a knife edge a short distance from a flat ended welding rule (Fig. 5.10).

5.7 Welding Parameters

The main parameters in RF welding are:

- power
- heating time
- cooling time
- weld depth
- pressure
- platen temperature

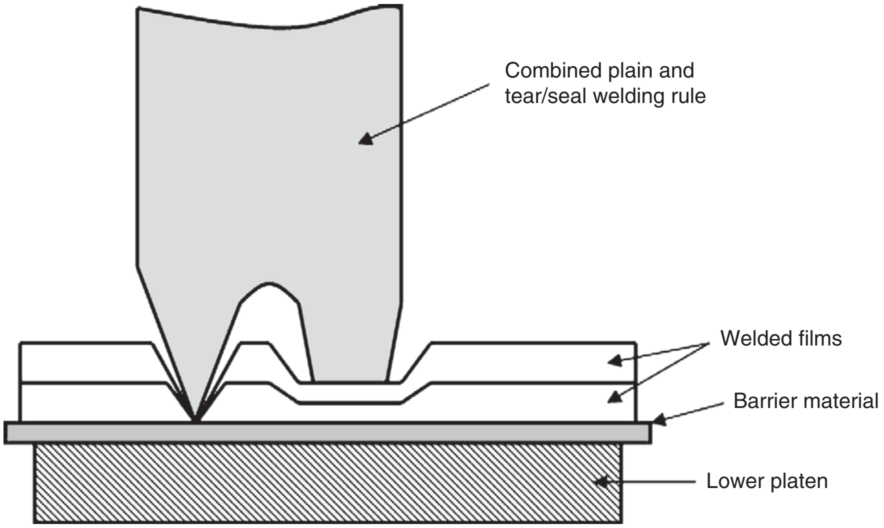

Figure 5.10. Combined plain and tear/seal welding (Source: TWI Ltd).

5.7.1 Power

The power required to produce a weld depends on a number of factors, including:

- Type of material: the higher the loss factor, the lower the power requirement.
- Thickness of material: the thicker the material, the lower the power requirement (due to reduced heat losses).
- Area of weld: the larger the weld area, the higher the power requirement.
- Required heating time: the shorter the required welding time, the higher the power requirement.
- Seam length: the longer the seam length, the higher the power requirement (a long, narrow seam requires more power than a short, wide seam of the same area).
- Barrier material: the use of a barrier material normally results in a lower power requirement (due to reduced heat losses).

Typically, a weld area between 10 and 30 cm^2 (2–5 in.^{2}) is achieved per kilowatt of RF power.

5.7.2 Heating Time

The heating time is the length of time for which the RF power is applied. The optimum heating time can be determined by monitoring the power during the heating phase; as soon as the power reaches a plateau or starts to fall, it indicates that the temperature at the weld is no longer increasing, and the power should therefore be switched off.

5.7.3 Cooling Time

This is the length of time for which the parts are held under pressure after the RF power is switched off. Since the electrodes are normally operating cold, the cooling time is quite short (typically around 20% of the welding time). However, this time may need to be increased during a production run since the tools will become hot over time.

5.7.4 Weld Depth

The weld depth controls how far the tooling penetrates into the parts during welding. This is more important when using plain seam welding.

5.7.5 Pressure

The welding pressure should be sufficient to allow the tooling to penetrate into the parts to the required weld depth. A higher pressure can result in shorter welding times; however, too high a pressure should be avoided, especially for tear/seal welding.

5.7.6 Platen Temperature

As mentioned above, if the temperature of the platen is not controlled, this may result in having to increase the cooling time during a production run due to the gradual increase in the temperature of the tooling. Having a thermostatically controlled platen temperature will result in a constant cooling time throughout a production run. It will also allow a larger area to be welded for a given power, due to reduced heat losses.

In addition, some materials, such as nylon and PET, cannot normally be RF welded unless the platens are heated.

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6 Hot Gas Welding

6.1 Process Description

Hot gas welding, also called hot air welding, is a manual process where the weld quality is dependent on the skill and experience of the operator.

During the welding process heated gas, usually air, is used to locally melt or soften both a consumable weld (filler) rod and the parts to be welded. Manual pressure is applied to the weld rod, either via the welding nozzle or by hand, and the combination of heat and pressure causes the weld rod and the parent material to fuse together; it is possible to achieve weld strengths of up to 90% of the parent material strength. The operator should maintain a consistent travel speed as the weld is made to ensure uniform heating. Critically, the weld rod and the parts to be welded must be made of the same thermoplastic and, ideally, should be of the same grade.

Before welding, the surface of the parts to be joined should be cleaned to ensure that any contamination, in the form of dirt, dust, or grease, is removed. The cleaned parts and the weld rod should then be scraped to remove any oxide layer and to ensure that a contaminant-free weld is achieved.

The heated gas is produced by a hot gas torch (or gun). The temperature of the gas stream is normally adjusted using a rheostat control in the handle of the welding torch, although some modern hot gas torches accurately regulate the temperature, ensuring that the output gas temperature is constant. The welding temperature (i.e., the temperature of the air coming out of the torch) should be set specifically to the type of material being welded. The use of welding temperatures outside the recommended range will result in a joint that is more likely to fail when exposed to chemicals, thermal cycling, solvents, or mechanical stresses. It is therefore recommended that a temperature calibration device should be used to guarantee that the correct gas temperature is being used. The volume of gas passing through the welding torch is typically 60 liters per minute.

All workshop welding should be undertaken on a wooden surface to prevent excessive heat loss from the joint; chipboard and medium density fiberboard (MDF) are ideal. Metal bench tops should be avoided as they act as a heat sink. All parts to be welded should be clamped securely to prevent movement while welding and during cooling. This allows the parts to relieve stress without distorting.

The hot gas welding process can be carried out by two methods: hand welding (also called pendulum welding, fan welding, slow-hand welding or free-hand welding), as shown in Fig. 6.1; or speed welding, as shown in Fig. 6.2.

In order to achieve hot gas welds of good strength, the position and grip of the operator's hand on the welding torch is important. For speed welding, the hand should be placed underneath the grip and pulled downward as the weld progresses (Fig. 6.3). This will maintain good control over the position of the welding

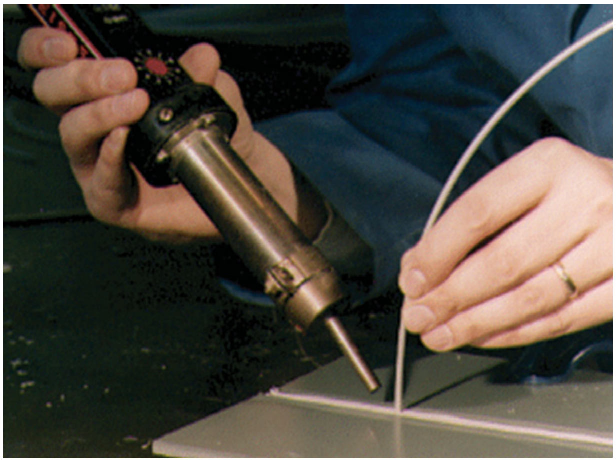

Figure 6.1. Hot gas hand welding (Source: TWI Ltd).

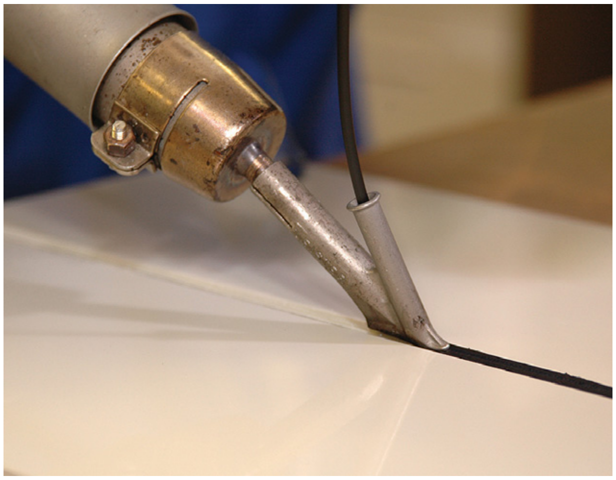

Figure 6.2. Hot gas speed welding (Source: TWI Ltd).

Figure 6.3. Hot gas welding hand position (Source: TWI Ltd).

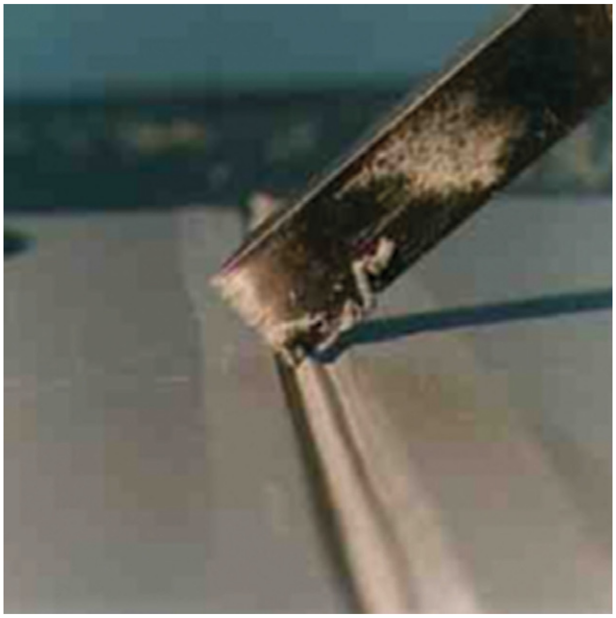

Figure 6.4. Scraping between weld runs (Source: TWI Ltd).

torch relative to the joint line. With repeated practice the balance of speed and pressure between weld rod and welding gun should ensure that a quality weld is achieved. For thicker joints, where more than one weld run is required, it is important to allow each weld run to cool. This prevents the polymer from overheating and reduces stresses in the material. The edges of the weld rod and the heat-affected surface of the weld preparation should be scraped prior to the application of each subsequent weld run (Fig. 6.4).

For hand welding, the weld rod is fed into the joint without the aid of a welding nozzle; the pressure is applied directly to the welding rod by the welder. This technique is ideally suited for welding small, complex components, since it allows for movement around the joint where a speed welding nozzle would not be able to fit. The nozzle of the welding torch is moved rapidly up and down the weld rod and along the joint line, heating both the joint surface and the weld rod as it progresses. When welding with this method, it is important to maintain a constant pressure on the weld rod and a constant travel speed along the joint. As weld pressure is applied by hand, the fingers can get uncomfortable and this could potentially compromise the weld strength. To overcome this problem, it is recommended that short relaxation breaks are taken. As in speed welding, cooling and scraping between each weld run is necessary.

In hand welding, the angle of the weld rod relative to the joint is also important (Fig. 6.5). For welding PVC, the weld rod should be at 90° to the sheet surface with a “bow wave” effect visible at the root of the weld rod. If the rod is bent back too much, stresses can be imposed on the surface of the weld rod and if subsequent runs are placed in the joint, the weld could relieve stress and split, causing unwanted gaps in the joint. If the rod is bent forward, the weld pressure will be difficult to maintain, which can result in a weak weld. For welding PP, the weld rod needs to be bent back to ensure a forward-welding motion is achieved. The “bow wave” effect should also be visible, as this shows that the weld has sufficiently penetrated into the parent material.

6.2 Advantages and Disadvantages

Hot gas welding can be used to weld practically any shape or size of component, and the equipment has probably the lowest cost of all the plastic welding techniques. Hot gas torches are very light and easy to use in awkward positions, and are ideally suited for field repairs where the component is too large to be transported into a workshop environment. However, welding speeds are relatively slow compared to other plastic welding techniques, and the weld quality is dependent

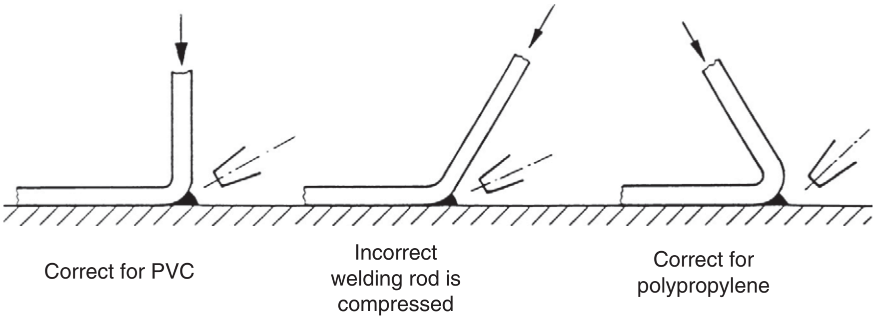

Figure 6.5. Hot gas hand welding rod angle (Source: TWI Ltd).

on the operator's skill. It is therefore important that hot gas welding operators are properly trained and certificated (e.g., to EN 13067 or AWS B2.4) [1, 2].

6.3 Applications

As hot gas welding is a manual process, it is not suitable for joining parts in mass production. However, it is ideal for fabricating various custom-made items, as it can be tailored for welding parts with any joint geometry. Examples of these include chemical storage tanks, ducting, fume extraction systems, and wet benches for the semiconductor industry. These items are difficult to fabricate using any other welding technique. Hot gas welding is used to weld thermoplastic membranes for roofing, lagoons, and linings for chemical vessels, and can also be used for repairing automotive parts such as bumpers and fluid reservoirs.

6.4 Materials

The most common thermoplastics joined by hot gas welding are PP, PE, PVC, and fluoropolymers (PVDF, FEP, PFA, and ECTFE). In most cases, the material used will be selected based on its chemical resistance, maximum working temperature and pressure, and on the design life of the finished product. Other materials that are hot gas welded include ABS, PC, acrylic, and polyamide. Also, hot gas welding is used for repairing automobile bumpers made from polycarbonate/polyester, PBT, or EPDM [3].

6.5 Equipment

Hot gas welding equipment consists of a gas source, hand grip, heater unit, and welding nozzle.

For hot air welding, the air can be compressed or blown. A blower is commonly used because it can supply a high air flow that is usually clean and moisture-free. If a compressor is used, it is essential that the air is dried and filtered before it reaches the welding torch, in order to prevent any potential contamination reaching the weld.

A blower can be either an integral part of the hot gas welding torch (Fig. 6.6) or a separate unit on a hose.

In fabrication workshop applications, where more than one torch is required and the work is primarily bench work, a single large blower can be used to supply several welding guns simultaneously. In this case, it is important to ensure that the blower is capable of supporting all the torches requiring the supply, without a drop in airflow.

For welding ECTFE some suppliers recommend using nitrogen as the gas medium. This is largely for health and safety reasons, as the fumes produced when welding in air can cause polymer fume fever. As an additional precaution, it is advised that local extraction is used, or that the welder wears a full face mask with a separate air supply.

The heating element is an electric coil wound around a ceramic core and is located inside the barrel

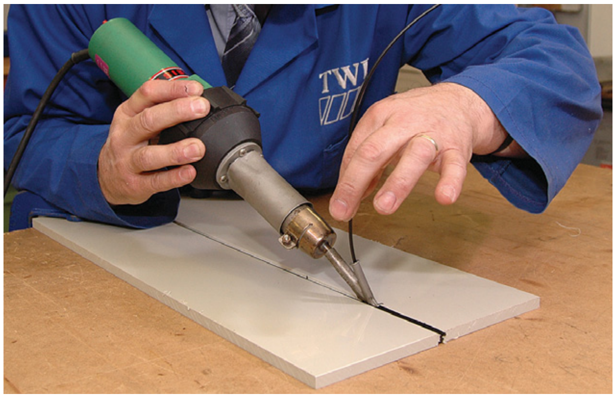

Figure 6.6. Hot gas welding torch with integral blower (Source: TWI Ltd).

of the welding torch. The gas temperature is usually set via a dial on the handle of the gun and is controlled by a diode, although in some equipment the temperature is set using a digital display on the handle of the gun and is controlled by using a temperature control microprocessor.

6.5.1 Welding Nozzles

Welding nozzles are interchangeable and are mounted at the front of the welding gun. There are three main types of welding nozzles: hand, speed, and tacking (Fig. 6.7).

For most applications, the tacking nozzle is used to hold the parts together before and during the application of the weld rod. As the tacking nozzle is moved along the joint, a stream of hot gas is expelled from the heel of the nozzle, heating and softening the parts to be welded. The toe of the tacking nozzle then forms the molten material into a localized weld. This tack weld has a low strength and should not be used as the sole means of welding parts together.

The hand-welding nozzle is used for welding operations where a conventional speed welding nozzle cannot be used. The end of the nozzle is usually 5 mm (0.2 inches) in diameter; however the length will vary depending on the application. During welding, the nozzle is held between 5 and 10 mm (0.2–0.4 inches) from the root of the weld and is manipulated in a pendulum motion up the rod and along the joint line.

The speed welding nozzle has a separate cylinder attached to the front of the nozzle, through which the weld rod is fed. There is also a small toe at the front of the speed nozzle, which helps to guide the weld rod into the joint line and applies the necessary pressure to force the rod into the joint. The hot gas for preheating the parent material is fed into the joint via a slot underneath the main body of the nozzle. The diameter and profile of the feeder tube is dependent on the shape and diameter of the weld rod. Speed welding nozzles are available for 3, 4, and 5 mm (0.12, 0.16, and 0.2 inches) diameter round weld rods, and 5.6 and 7.4 mm (0.22 and 0.29 inches) triangular weld rods.

6.6 Joint Design

Where butt-welded joints are to be made for materials less than 6 mm (0.24 inches) thickness, the sheet edges should be prepared in the form of a single V at an angle of between 60 and 80° (Fig. 6.8a). For fabrications where the sheet thickness is greater than 6 mm (0.24 inches), the preparation of the joint should be a double V (Fig. 6.8b). In both cases, the number of weld runs should be sufficient to fill the prepared joint; if required, the weld can be dressed to a smooth finish, leaving no indents or grooves on the surface of the component. This is important for food or laboratory applications, where a contamination-free surface is required.

Figure 6.9 shows examples of different T-joint configurations. Sheet thickness and specific customer requirements usually determine which joint is selected. Figure 6.10 shows a typical design for a corner joint.

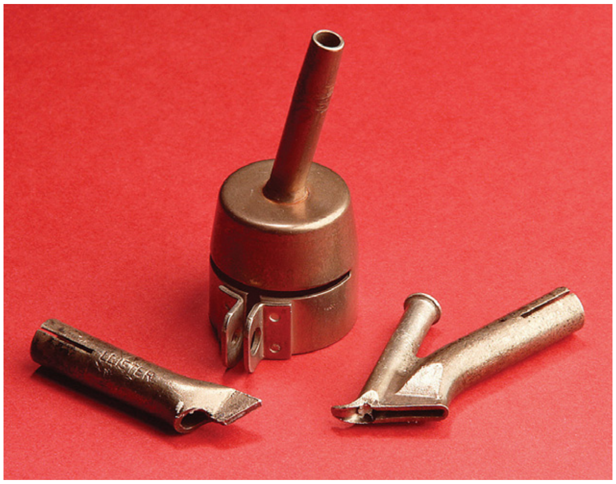

Figure 6.7. Hot gas welding nozzles: tacking (left), hand (center), and speed (right) (Source: TWI Ltd).

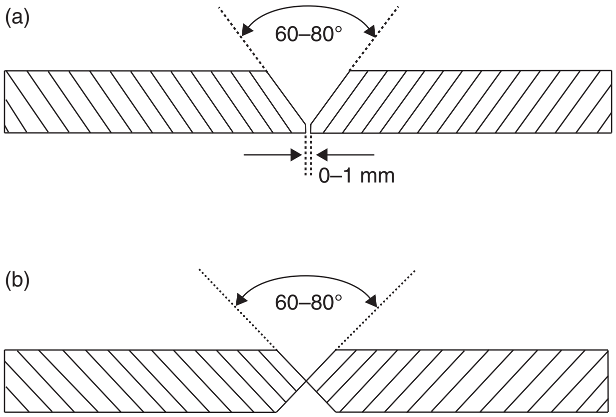

Figure 6.8. Typical hot gas butt joint weld preparations: (a) single V; (b) double V (Source: TWI Ltd).

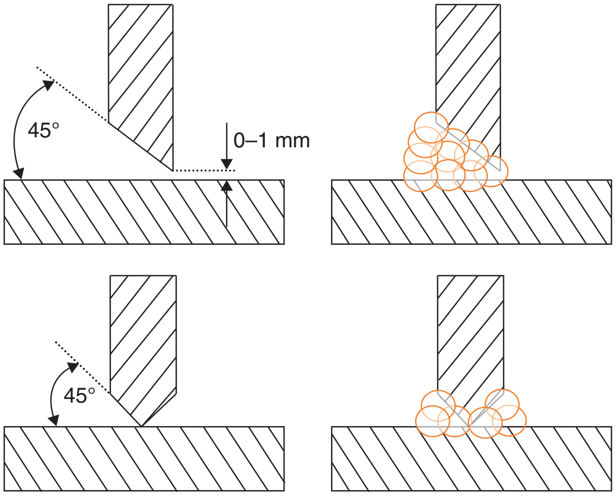

Figure 6.9. Examples of T-joints for hot gas welding (Source: TWI Ltd).

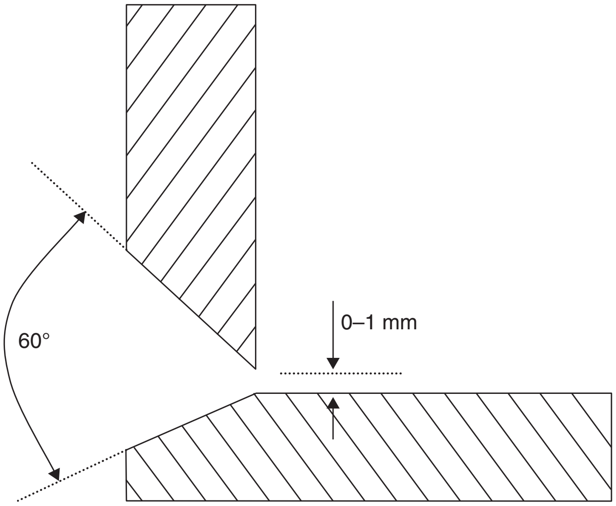

Figure 6.10. Typical corner joint preparation for hot gas welding (Source: TWI Ltd).

6.7 Welding Parameters

There are four main parameters for hot gas welding: temperature, pressure, speed, and torch position. It is essential that the operator has the necessary knowledge to implement and monitor each welding parameter effectively. Failure to do so could result in the fabrication of a weak weld.

Welding temperature is the most important welding parameter, although the temperature at the joint surface depends not only on the temperature of the gas coming out of the welding torch but also on the welding speed and the position of the welding gun in relation to the joint.

The optimal gas temperature will depend on the material being welded, and the recommended welding temperature range should be obtained from the material manufacturer. Before welding, the temperature should be measured using a temperature calibration tool, 5 mm (0.2 inches) inside the nozzle, in the center of the air stream (Fig. 6.11).

It is important to allow the temperature of the gas flow to stabilize after setting the hot gas temperature. This typically takes around ten minutes, although on microprocessor controlled equipment, temperature stabilization will be quicker. On completion of the welding operation, the set temperature should be reduced to zero with the gas supply left running. This will allow the heating element to cool naturally, preventing damage to the torch, and helping to prolong the life of the heating element.

The welding pressure is one parameter of the welding process that can be difficult to control, since welding pressure is always applied manually. Repeated practice of hot gas welding on a pressure sensitive table is one method of ensuring that a consistent welding pressure is achieved. For speed welding, fusion takes place by applying pressure to the weld rod by hand and simultaneously applying pressure to the toe of the nozzle. This is done by pulling down on the handle of the welding gun. For hand welding, only manual pressure is applied to the weld rod.

The welding speed is partly governed by the temperature setting of the torch, the type of material being welded, and the diameter of the weld rod. The speed should be sufficient for the surface of the prepared joint and weld rod to soften. If the correct travel speed is

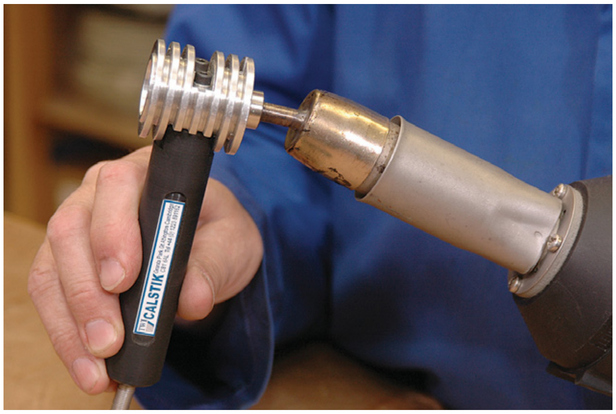

Figure 6.11. Hot gas torch temperature calibration device (Source: TWI Ltd).

used, a bead should appear along the edge of the weld run. In the case of PVC, a glossy, smooth surface texture should be apparent and, in the case of PP and PE, a slight flat on the surface of the weld bead and a distinct smooth texture should be visible. No charring or discoloration should be apparent along the weld, and the filler rod should not be stretched during welding.

The angle of the welding gun in relation to the joint is also a very important welding parameter, since an even preheat will ensure that the parent material is softened sufficiently, ensuring a full penetration weld is made. For multi-pass welding, the gun angle will vary depending on which weld run is being applied. The type of joint configuration will also affect the angle of the welding gun.

6.8 Variants of Hot Gas Welding

6.8.1 Manual Lap Welding

Hot gas welding is also used for joining membrane materials, such as PE, PP, and PVC, without the use of a filler rod. The principle of this technique is that hot air is introduced between the two sheets to be joined by means of a flat (fish-tail) nozzle, which subsequently melts the two surfaces. The nozzle is moved between the sheets at a constant speed and pressure is applied immediately behind the nozzle by means of a hand-held roller or some other blunt instrument that will not damage or puncture the liner (Fig. 6.12). The combination of hot air and applied pressure results in the two liners being welded together.

The two surfaces to be joined should be cleaned to remove any contamination, such as dirt or dust, prior to welding. The welding temperature and rate of seaming will vary according to the membrane type and thickness, and ambient conditions. If the temperature is too high or the welding speed too low, this will result in excessive melt generation and/or surface deformation.

6.8.2 Automatic Hot Gas Welding

Automatic hot gas welding machines are also available for lap welding of membranes (Fig. 6.13). The pressure and drive rollers, which are usually knurled, apply pressure to the seam and move the machine along as welding proceeds. A drive motor, which uses a chain drive system similar to a wedge welding machine, powers the rollers. As heated gas is blown between the membranes through a nozzle, escaping gas preheats the material to be sealed, and small particles (stones, sand, dust, etc.) are blown away from the surface. Hot gas

Figure 6.12. Hot gas lap welding of PVC membrane (Source: Leister Process Technologies).

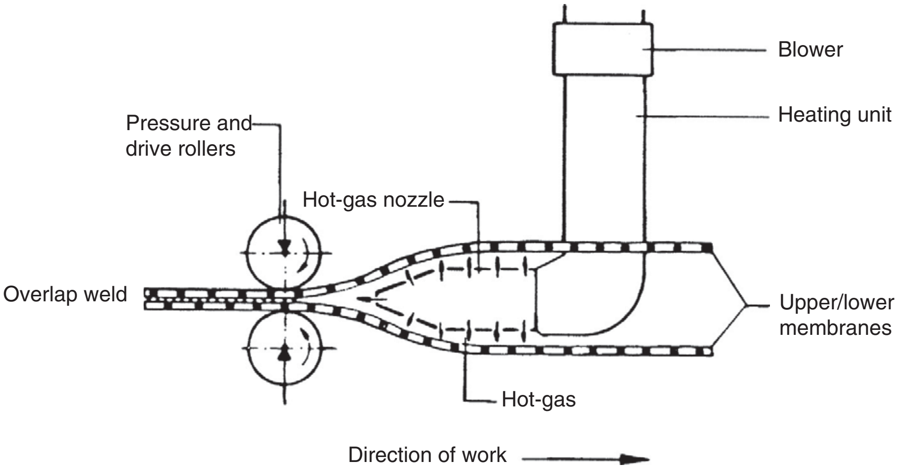

Figure 6.13. Diagram of an automatic hot gas welding machine used for sealing membrane seams.

emerges at the tip of the nozzle, causing the thermoplastic sheet material to melt and flow. As new material is fed through the pressure and drive roller, the melted seam cools, and solidifies.

There are two main types of airflow nozzles; one for producing a single track and another for producing a double-track seam. If a double-track seam is required, the nozzle is subdivided at its exit end into two separate airflow channels.

Temperature controllers on the machine should be set according to the type of membrane being welded, the ambient temperature, and the rate of seaming. A welding speed of 4 m/minute (13 feet/minute) is typical. Automatic hot gas welding produces a consistent, reproducible, high quality weld [4].

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7 Extrusion Welding

7.1 Process Description

Extrusion welding is an established plastics-joining technique that was developed in the early 1960s for the fabrication of thermoplastic structures. It is used commercially to weld PP and HDPE, although specialized equipment is available for welding PVC and PVDF. Extrusion welding is usually performed manually, although it can be automated for continuous welding applications. The technique involves continuously extruding molten thermoplastic (extrudate) of the same material (and ideally of the same grade) as the parts being welded, into a prepared joint between the parts, using an extrusion welding gun (Fig. 7.1).

The joint (weld preparation) is preheated to its softening temperature by a stream of hot air before the extrudate is forced into the joint under pressure. This ensures that the extrudate and the parts fuse together and produce a weld (Fig. 7.2).

As for hot gas welding, the parts to be joined should be cleaned, scraped, and machined to produce a V-groove joint preparation. Using a hot gas gun fitted with a tacking nozzle, the two parts to be welded are initially tacked together. In addition, a hot gas weld should also be applied to the root of the weld preparation. This will ensure a full root penetration weld and restricts any movement of the parts during the extrusion welding process. Alternatively, a clamping system can be used to hold the two parts during welding.

Figure 7.1. Extrusion welding of thermoplastic sheet (Source: TWI Ltd).

Before welding, it is important to check the temperature of the extrudate and preheat air to ensure that the actual temperatures are the same as those set on the temperature controller of the extrusion welding machine. The extruder should also be purged, so that any overheated or degraded material left in the barrel from the previous welding operation is cleared.

At the start of a weld run, the operator preheats the parts by gently moving the extrusion welding gun backward and forward along the joint. If this is not done, the extrudate will be deposited onto cold material, resulting in a poor-quality weld. The extrusion welding gun should be held at the correct angle both longitudinally and laterally to ensure that an even preheat is maintained and a smooth surface finish is produced. The forward motion is achieved by manually pushing downward and forward on the extruder, with the welding speed governed by the output rate of the extrudate.

7.2 Advantages and Disadvantages

The most significant advantage of using the extrusion welding process, when compared to hot gas welding, is that a continuous weld bead is formed in a single pass, compared to multiple passes for hot gas welding and, due to the increased volume of material dispensed, the fabrication times are significantly shorter than for hot gas welding. In addition, the maximum weld strength is higher than for hot gas welding, as closer control of the welding parameters is achievable.

The most significant disadvantage of the extrusion welding process, compared to hot gas welding, is the weight and size of the equipment; some extrusion welding guns can weigh in excess of 12 kg (26 lb). Vertical welding can therefore become very uncomfortable for the operator. Also, welding internal corners and welding in confined spaces is difficult, due to the size of the equipment. In addition, as with hot gas welding, since the quality of the weld is dependent on the skill of the operator, it is important that extrusion welding is carried out by properly trained and certificated operators.

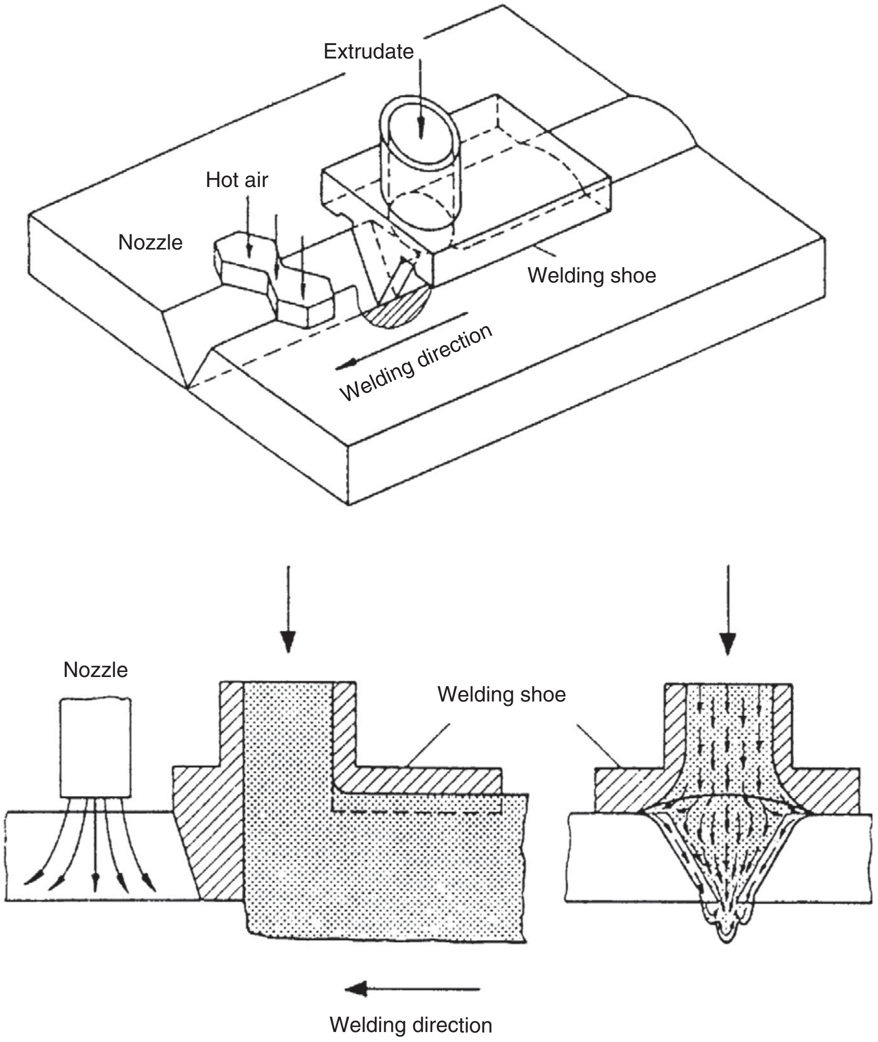

Figure 7.2. Schematic of extrusion welding process.

7.3 Applications

Extrusion welding is used in the manufacture of large thermoplastic fabrications, such as tanks and pipe sections, where it is necessary to produce large volume, homogeneous welds in a single pass (Fig.7.3).

Extrusion welding is also used in environmental applications, such as the joining of lining material for the construction of landfill waste sites, lagoons, and roof coverings (Fig. 7.4). The technique is increasingly used in agriculture and water engineering applications such as the fabrication of land drainage systems, sump tanks, and man ways (Fig. 7.5).

7.4 Materials

Extrusion welding is used primarily for welding PP and PE, although some extruders have been designed specifically for welding PVC and PVDF. In the case of PVC, due to its narrow processing temperature range, the extruder should be purged after each weld run with PP or PE to ensure that no PVC material is left in the barrel to overheat and degrade.

7.5 Equipment

The main components of an extrusion welding gun are shown in Fig. 7.6. The drive motor (1) is an electric drill with improved gearing, which drives a screw shaft in a heated barrel. This also feeds the welding rod (2) into the rod input point via a pair of pinch rollers (3), and then into the extruder (4). Modern extruders have a special welding rod feed, which prevents the welding rod from becoming twisted, and ensures constant rod input. This improves the uniformity of the welding

Figure 7.3. Extrusion welding of a large pipe section (Source: Leister Process Technologies).

Figure 7.4. Extrusion welding a HDPE liner on a landfill site (Source: TWI Ltd).

Figure 7.5. An extrusion welded storm water storage vessel (Source: TWI Ltd).

seam, since variations in input due to kinks and twists in the weld rod will lead to variations in output. The extruder screw grinds the welding rod into granules, which are then fed into the melting chamber (5) where they gradually melt. The material then continues through the heated barrel until it leaves the extruder through a PTFE shoe (6), which forms the shape of the seam required. The parts to be welded are heated by the heating nozzle (7) with air supplied (on this particular design) via an integral air heater unit (8).

Certain machines also have the facility to be fed with granulate directly, rather than welding rod. These extruders are mainly used in landfill applications where very long seams are often required. The hoppers can be covered to reduce the possibility of moisture and particulate contamination getting into the feedstock. Typical extrusion welding speeds of 0.5–1.0 m/minute (1.6–3.3 ft/minute) are achievable.

There are many variations of welding shoe, each made for specific weld geometries and applications. Examples of different welding shoes are shown in Fig. 7.7.

7.6 Joint Design

As for hot gas welding, the butt joint weld preparations for extrusion welding can be in the form of a single V or double V (Fig. 7.8). The joint designs for a T-joint and an overlap joint are given in Figs. 7.9 and 7.10, respectively.

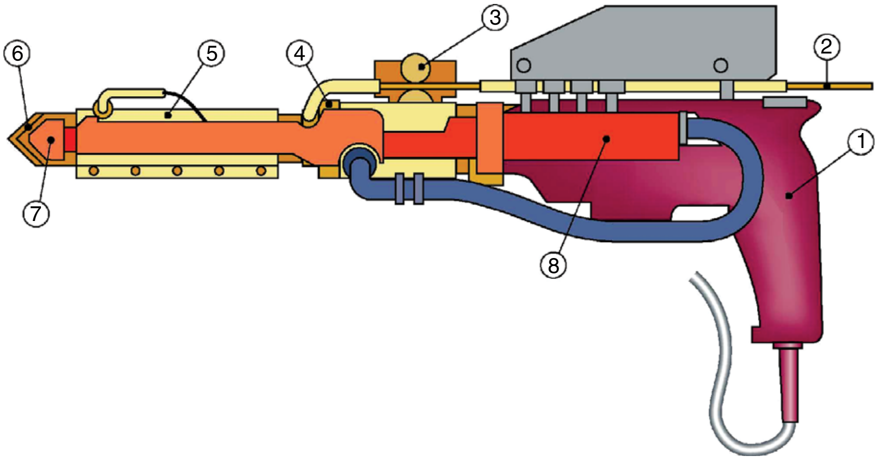

Figure 7.6. Schematic of extrusion welding gun (Source: TWI Ltd).

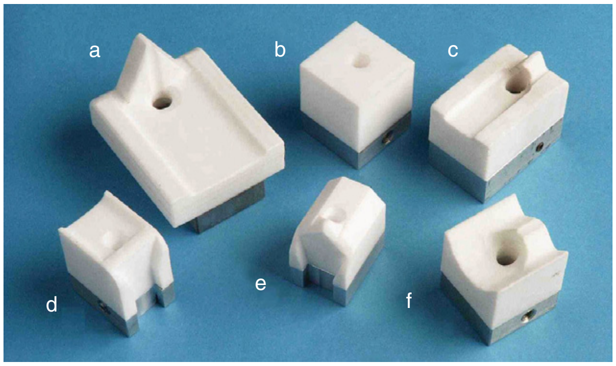

Figure 7.7. Examples of extrusion welding shoes: (a) for a butt weld in thick section sheet; (b) a blank, to enable the welder to shape a shoe for a specific joint; (c) for butt welds in sheet up to 15 mm (0.6 inches) thick; (d) for welding lining material, geomembranes, pond liners, lagoons, etc; (e) for a fillet weld; and (f) for producing a corner weld profile (Source: TWI Ltd).

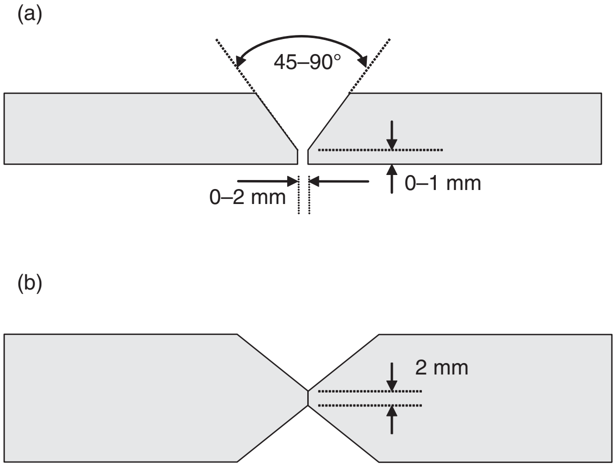

Figure 7.8. Typical extrusion welding butt joint designs: (a) single V; (b) double V (Source: TWI Ltd).

7.7 Welding Parameters

The main parameters in extrusion welding are:

- Extrusion rate.
- Temperature of the extrudate.
- Preheat air flow rate.
- Preheat air temperature.
- Welding speed.
- Position of the welding gun.

The maximum welding speed that can be achieved is dependent on the extrusion rate, the material thickness, the cross-sectional area of the seam, and the size and design of the PTFE welding shoe.

Typical extrusion welding temperatures for PP should be in the region of 230°C (446°F) for the extrudate and 250°C (482°F) for the preheat gas. For HDPE, the extrudate temperature should be around 240°C (464°F) and the preheat gas temperature should be around 260°C (500°F). These temperatures will vary, subject to the ambient conditions and type of extrusion welding machine used. Prior to commencing the welding operation, it is recommended that trial welds are made and tested, in order to optimize welding conditions. Figure 7.11 shows a fillet weld where the correct welding parameters have been used; Figure 7.12 shows an extrusion weld where incorrect welding parameters have been used.

The weld cooling rate will also have an effect on the joint strength; where possible, the weld should be allowed to cool naturally. Forced cooling will result in a crystalline structure that is more likely to generate failure when exposed to chemicals or stress.

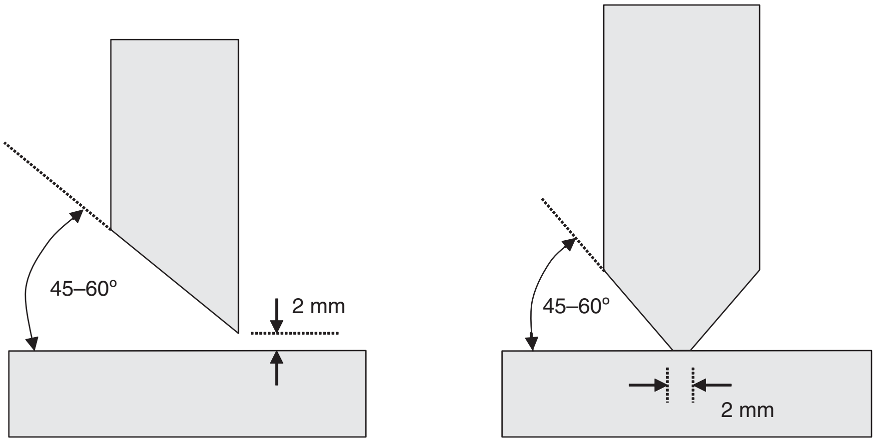

Figure 7.9. Examples of T-joints for extrusion welding (Source: TWI Ltd).

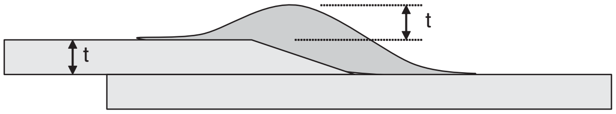

Figure 7.10. An overlap joint for extrusion welding lining membranes (Source: TWI Ltd).

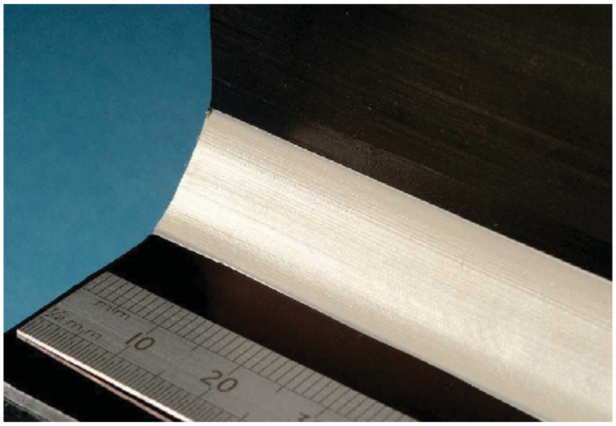

Figure 7.11. Extrusion fillet weld using the correct welding parameters (Source: TWI Ltd).

7.8 Variants of Extrusion Welding

7.8.1 Discontinuous Extrusion Welding

This method involves the manual transfer of an extrudate rod to the joint (Fig. 7.13). In this process a length of extrudate rod is collected from a high-output extruder in a flexible PTFE tube (Fig. 7.13a) and is then laid into the joint, which has been preheated using a hot gas torch (Fig. 7.13b), and is then forced into the joint using a pressing tool or roller (Fig. 7.13c).

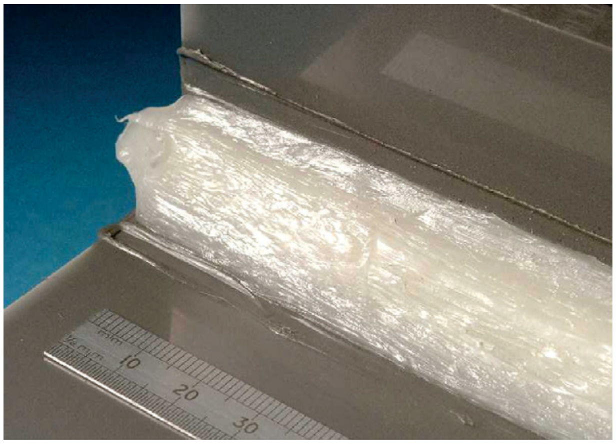

Figure 7.12. Extrusion fillet weld using incorrect welding parameters (Source: TWI Ltd).

7.8.2 Stationary Extruder/Movable Welding Head

In this method (Fig. 7.14), the extrudate is transferred from the extruder to a welding head via a heated flexible tube. A hot gas torch, which is also located on the welding head, provides the preheat.

7.8.3 Sheet Extrusion Welding

This system, which produces a lap weld between two thermoplastic sheets, consists of a motor-driven trolley, which carries the extruder and also provides the welding pressure via a set of rollers. Also attached to the trolley is a hot gas torch, which is inserted into the overlap to preheat the sheets in front of the extrusion die, which extrudes filler material between the sheets (Fig. 7.15).

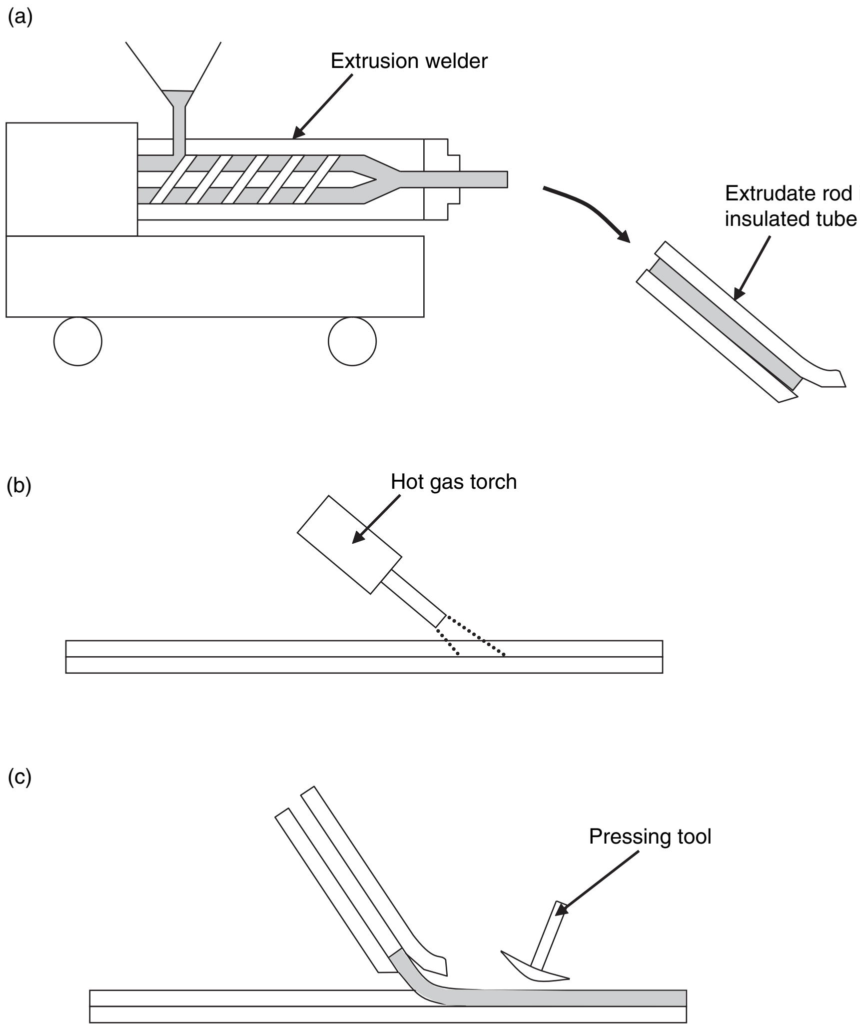

Figure 7.13. Discontinuous extrusion welding process (Source: TWI Ltd).

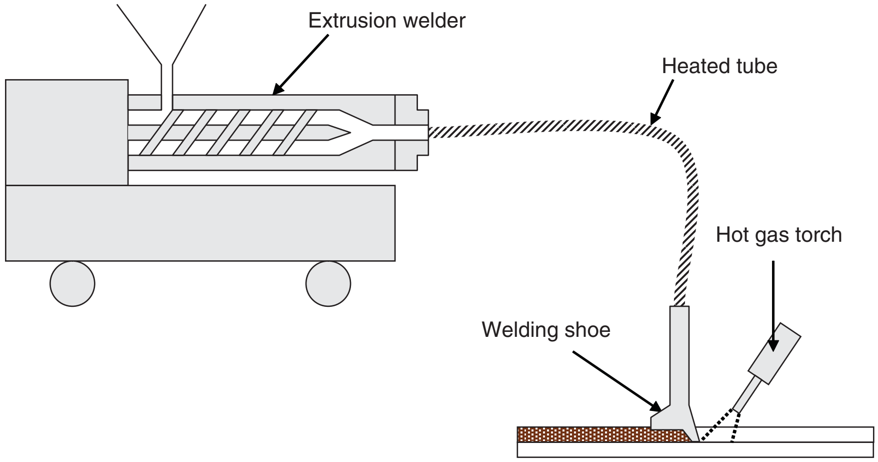

Figure 7.14. Stationary extruder with movable welding head (Source: TWI Ltd).

7.8.4 Injection Welding

In injection (Injectiweld) welding, a hand-held gun is used to inject molten thermoplastic under pressure into the joint area to form a weld, without the use of hot air or gas; the parts to be welded are heated by direct contact with the heated tip of the gun, which is submerged into the surface of the parent material. To ensure that a good weld strength is achieved, the tip

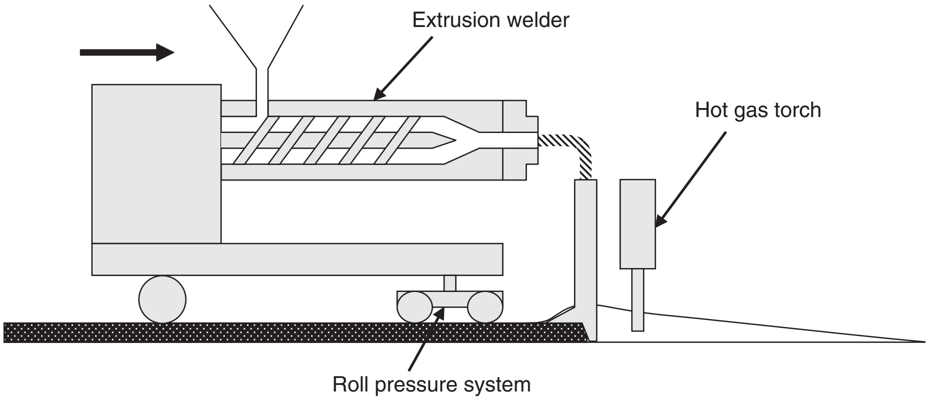

Figure 7.15. Sheet extrusion welding process (Source: TWI Ltd).

Figure 7.16. Interchangeable tips for injection welding (Source: Drader Injectiweld Inc.).

Figure 7.17. Injection welding (Source: Drader Injectiweld Inc.)

should maintain contact with the parent material at all times. Various interchangeable welding tips are available, depending on the application (Fig. 7.16).

The Injectiweld gun has an automatic feed system, enabling an operator to use the machine with one hand (Fig. 7.17). Typical applications for injection welding include: the repair of thermoplastic components, fabricating plastic parts, and welding lining materials. One significant advantage of injection welding is that the welding gun is small enough to reach internal corners and other areas that are difficult to weld using the extrusion welding process. Another advantage is that with this process, the removal of surface oxidation is normally not necessary.

8 Laser Welding

8.1 Process Description

8.1.1 Introduction

Laser welding was first demonstrated for thermoplastics in the 1970s, and since the late 1990s it has been used in mass production. The technique, suitable for joining both sheet, film, molded thermoplastics and textiles, uses a laser beam to melt the plastic in the joint region. Lasers are well suited to delivering controlled amounts of energy to a precise location due to the ease of controlling the beam size available (10 μm–100 mm width), and the range of methods available for precise positioning and movement of the beam. Two general forms of laser welding exist: direct laser welding and transmission laser welding.

8.1.2 Interaction of Light with Polymers

When radiation strikes a material surface some energy will be reflected, some absorbed, and some transmitted. For laser materials processing the energy must be absorbed efficiently in the correct location. The type of interaction of the beam with the surface will depend on the following factors:

- Type of material and additive content, including the effect of surface coatings.
- Laser wavelength.
- Laser intensity (power, spot size or shape, beam quality).
- Rate of movement of the beam over the surface.

When laser radiation is absorbed into a polymer surface, the interaction can be one of two types depending on the wavelength:

- Short wavelength radiation (less than 350 nm or ultraviolet (UV)) gives rise to *photolytic* processes in which the photon energy is high enough to directly break chemical bonds. This is sometimes described as cold processing and can be used for ablation, chemical curing, or other chemical changes such as marking via a color change.
- Long wavelength radiation (longer than 350 nm and extending into infrared (IR)) gives rise to *pyrolytic* processes which involve heating. This can be used for melting and hence for welding, or at higher intensity for vaporization or thermal degradation, for example, as used in laser cutting.

In addition to energy absorption, polymers also scatter light. This is particularly relevant for semicrystalline polymers where the spherulites are often of a suitable size to scatter UV, visible, or IR radiation.

The long wavelength radiation absorption characteristics of a typical polymer are shown in Fig. 8.1,

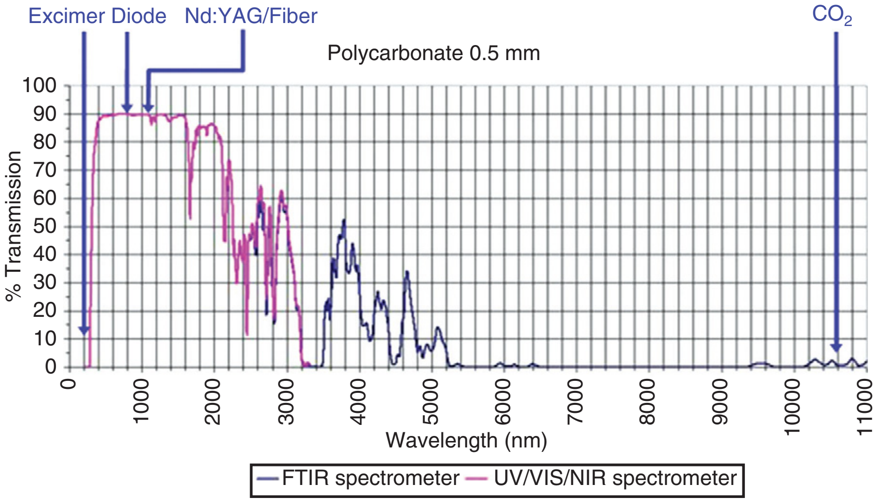

Figure 8.1. Transmission spectrum for 0.5 mm (0.02 inches) thick polycarbonate showing the major laser types (Source: TWI Ltd).

where it can be seen that there is a band, from approximately 400–1600 nm, where there is very little absorption (i.e., high transmission). Diode, fiber, and Nd:YAG lasers therefore transmit readily through the polymer and can be used for transmission laser welding. CO_2 lasers, however, are absorbed rapidly into the surface and can be used for cutting or film welding in a direct heating process.

Finally, the variation in absorption between different polymers and the effect of additives should be considered. Figure 8.2 shows the transmission properties for different polymers at a range of thicknesses. Semicrystalline polymers such as nylon, PE, and PP show rapidly diminishing transmission with thickness. A small addition of carbon black pigment reduces the transmission effectively to zero. These effects are important in welding. Carbon black and other IR absorbers can be placed in locations where heating or welding is wanted. This allows transmission laser welding to be carried out if the absorber is in or on the surface of the lower material, but not in the top material.

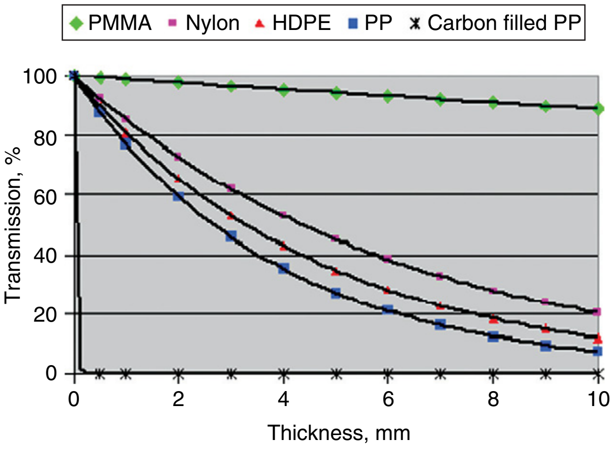

Figure 8.2. Relationship between laser transmission and thickness for different polymers (Source: TWI Ltd).

8.1.3 Direct Laser Welding

In direct laser welding (Fig. 8.3) the materials are heated from the outer surface possibly, to a depth of a few millimeters. Normally, no specific radiation absorber is added to the plastics. Laser sources of 2.0–10.6 μm wavelength are typically used. At 10.6 μm (CO_2 laser), radiation is strongly absorbed by plastic surfaces, allowing high-speed joints to be made in thin films. Developments have also been made using a CO_2 laser transmissive cover sheet as a clamp and heat-sink to make welds in thicker plastics without material loss at the surface. At 2.0 μm, where the absorption is less strong, a fiber or Holmium:YAG laser can be used to make welds in sheet a few millimeters thick. Direct laser welding is not widely applied for joining plastics, but it has a potential for wider use [1–3].

8.1.4 Transmission Laser Welding

Transmission laser welding is now widely used for joining thermoplastics in industry, using laser sources

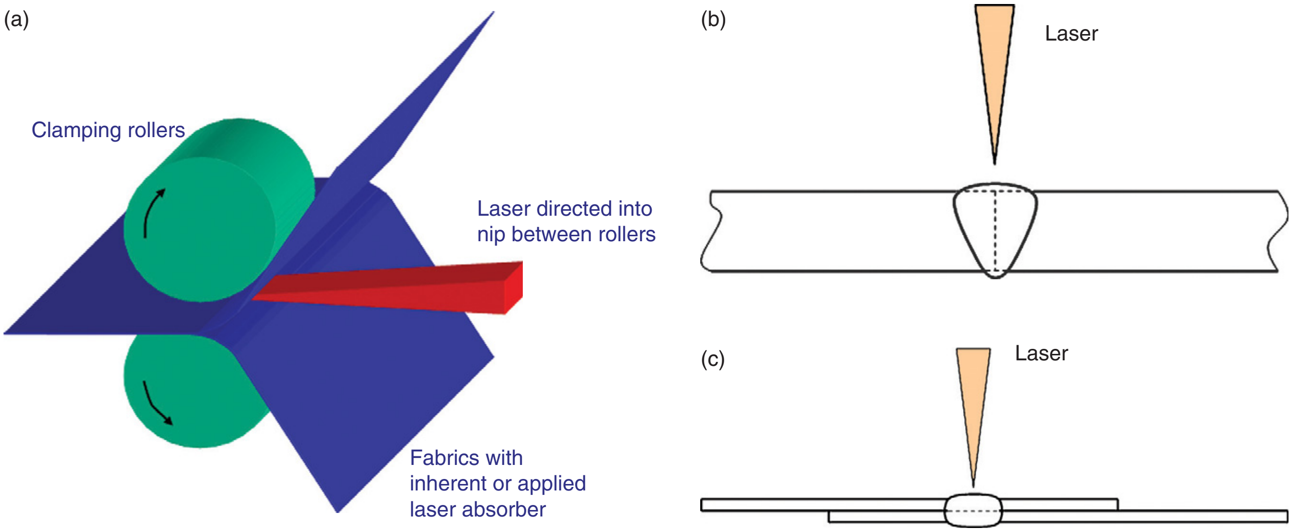

Figure 8.3. Direct laser welding formats: (a) welding into a nip between rollers, (b) butt welding, and (c) overlap film welding (Source: TWI Ltd).

with wavelengths from 0.8–1.1 µm, such as diode, Nd:YAG, and fiber lasers. The radiation at these wavelengths is less readily absorbed by natural plastics. Laser absorbing additives are therefore put into the lower part or applied as a thin surface coating at the joint. The parts are positioned together before welding and the laser beam passes through the upper part to heat the joint at the absorbing surface of the lower part (Fig. 8.4). The absorber in or on the lower plastic is typically carbon or an IR absorber with minimal visible color, such as Clearweld®, which allows a wide range of part colors and appearances to be welded. Transmission laser welding is capable of welding thicker parts than direct welding, and since the heat affected zone is confined to the joint region, no marking of the outer surfaces occurs [4].

The maximum thickness of the upper part is determined by the transmission properties of the material; transmission laser welding is only possible if over 10% of the energy is transmitted to the joint interface.

Transmission laser welding can also be used to weld film and sheet materials. The laser source is scanned over the two parts just in advance of clamping, using a roll-processing method.

Examples of transmission laser welded parts are shown in Fig. 8.5.

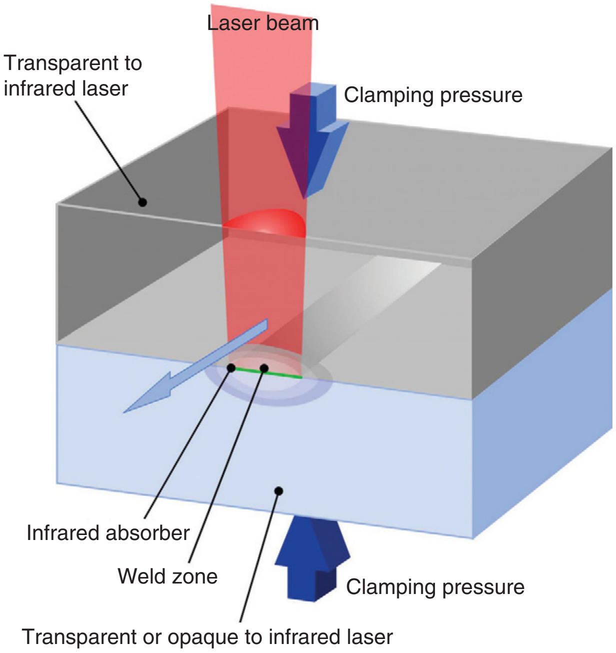

Figure 8.4. Diagram of transmission laser welding, showing the movement of a beam over a workpiece. The lower part can be arranged to be an infrared absorber or the absorber can be placed at the joint interface (Source: TWI Ltd).

Figure 8.5. Parts welded using transmission laser welding with carbon black absorber (center) and Clearweld absorber (Source: TWI Ltd).

8.2 Advantages and Disadvantages

The advantages and disadvantages of transmission laser welding are summarized in Table 8.1.

8.3 Applications

Laser welding is used in a wide range of application areas, including:

- Electronic packages
- Textiles
- Biomedical devices
- Windows and signs
- Food and medical packaging
- Visual displays
- Automotive components

8.3.1 Film and Sheet

Direct laser welding can be used to make small welds in thin materials at high speeds. Figure 8.6 shows an example using a CO_2 laser for welding PE film [1].

8.3.2 Molded Parts

Automotive: The use of laser welding in automotive applications has risen rapidly because it allows high speed, automated production, and excellent consistency

Table 8.1. Advantages/Disadvantages of Transmission Laser Welding

Advantages	Disadvantages
Automated process	The top part must transmit the laser radiation
Good monitoring and quality control procedures	Laser absorbing material must be added to one of the plastics or at the joint surface
Joint designs are simple flat to flat surfaces in general	Equipment can be expensive
Hermetic seals possible	Joint surfaces must be of good quality.
Fast (<1 s) weld possible depending on size	Part clamping must be designed carefully to ensure contact during welding.
No contact with heated tools	Health and safety issues relating to the use of lasers
No vibration	Part thickness limitations, especially for highly crystalline materials, such as PEEK
No particulate generation	
Precise placement of welds (50 μm or less)	
No surface damage	
Low residual stresses	
Complex shapes possible	
Localized heating—no thermal damage close to weld	
Multiple layers can be welded simultaneously	
Thin, flexible substrates or elastomers can be welded	
Suitable for high melting point polymers and those with low melt viscosities, such as polyamides	
Can join dissimilar materials by using a compatible IR-absorbing interlayer	
Little or no flash	

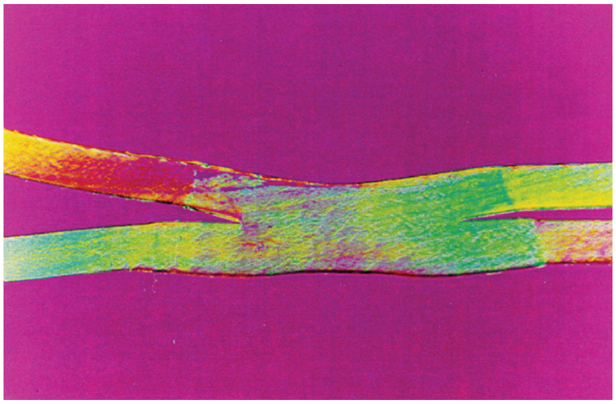

Figure 8.6. CO_2 laser weld in 100 μm (0.004 inches) polyethylene film at 100 m/min (328 ft/min) with 100 W laser power. The weld is approximately 0.5 mm (0.02 inches) wide and was heated from the top (Source: TWI Ltd).

of quality. This combination leads to cost reduction in many application areas. It has been used in areas such as license plates, door handles, displays, electronic keys, water pumps (pressure container), pneumatic valves and light clusters, and it has been evaluated for attachment of carpet panels to rigid plastics. Laser welding for body panels in an 'all-plastic' car is also being considered [5].

Industrial: Laser welding has been used to join nylon 12 gas pipes, and has replaced hot gas welding in the construction of lithographic processing tanks (Fig. 8.7) [6, 7].

Medical: By using the Clearweld technology, completely transparent products can be laser-welded, which is of particular importance in the medical industry. An example of a laser-welded transparent medical device is shown in Fig. 8.8 [8].

Micro-welding: Of the various available plastics welding methods, laser welding is best suited for making welds with dimensions less than 1 mm (0.04 inches). Manipulation equipment is available to position components (and the laser source) to an accuracy better than 1 μm, and Nd:YAG, fiber, and diode lasers can be focused down to spot sizes less than 100 μm (0.004 inches) wide [9, 10].

A spin coating of IR absorber dye has been used to weld 250 μm (0.01 inches) thick polycarbonate foils using an Nd:YAG laser. Capillary gel electrophoresis chips made of PMMA and containing 300 channels with 50 μm (0.002 inches) width and depth have been

Figure 8.7. Laser welding of a polypropylene lithographic processing tank (Source: TWI Ltd).

Figure 8.8. PMMA medical device, welded using a Clearweld coating (Source: TWI Ltd).

sealed by welding a film over the channels using a 15 mm (0.6 inches) wide diode laser line source. A microfluidic device, with channel widths of 100 μm (0.004 inches) was welded using a laser masking system. Low power (<1 W) fiber-coupled laser diodes are also available that provide a focused spot width of 25 μm (0.001 inches), and have been used to produce weld widths of 50 μm (0.002 inches) in clear to carbon black-filled polycarbonate [11–14].

Microtiter components have been sealed with an 80 μm (0.003 inch) wide diode laser source. The seals provide higher quality than similar samples that had been adhesively bonded. Low-power diode laser sources have been reported to give welding seams as narrow as 10 μm in PETG. A process using a thin carbon coating (5–20 nm) as an absorber has also been developed for welding channels in the 100 μm (0.004 inch) size range. It was also suggested that smaller features (10–30 μm), and potentially multilayer structures could be welded in the same way [15–17].

An alternative approach, where the microchannels are filled with sacrificial material during the welding process, can lead to internal surfaces free of flash, and can allow interchannel wall widths at least as small as 40 μm (0.0016 inches). The sacrificial material is washed out of the channels after welding [18].

8.3.3 Textiles

Fabrics are most commonly joined by stitching, a highly labor-intensive process that renders production cost-prohibitive in many parts of the world. It also results in holes in the fabric, which impairs the strength of the resulting seam and limits the performance of seams that need to be sealed.

The principal advantages of laser welding for joining textiles include high production rates, sealed seams, no melting of external fabric texture, single-sided access so welds can be produced beneath other layers of fabric, seam flexibility, and robotic manipulation for automated joining.

Applications such as airbag construction, bed assembly, medical furniture, and clothing (Fig. 8.9) have been studied, with successful demonstration of representative seams that meet the performance requirements of the applications [19].

The laser welding procedure used for textiles is generally based on the Clearweld method of transmission laser welding, but direct welding using either diode or CO_2 laser sources is also feasible.

An example using a diode laser manipulated by a six-axis robot is shown in Fig. 8.10, where speeds of

Figure 8.9. Woven polyester shirt with laser welded seams (Source: TWI Ltd).

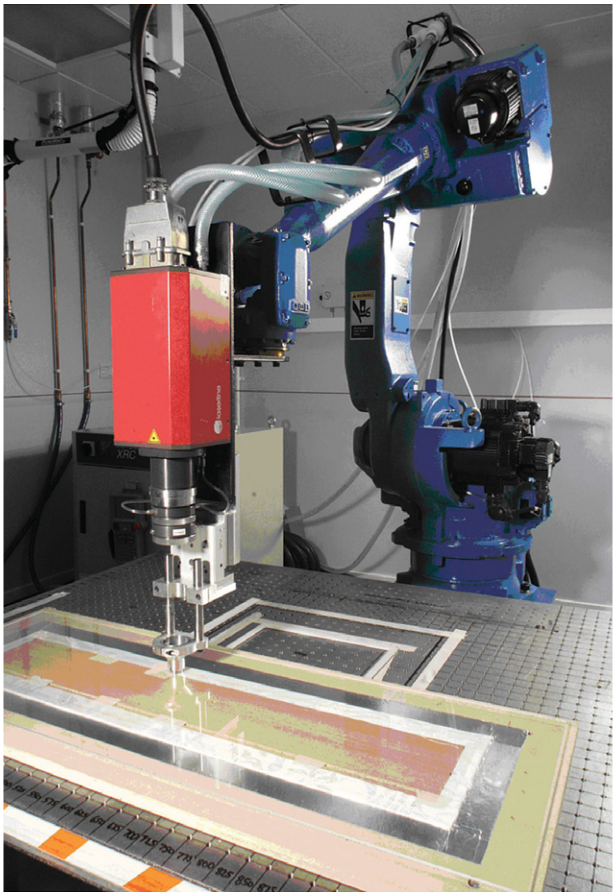

Figure 8.10. Robotic manipulation of diode laser welding upholstery to PVC-coated wooden divan drawer (Source: TWI Ltd).

3–10 m/min (10–33 ft/min) were attained, depending on the laser power and the type of fabric. A satisfactory weld microstructure is shown in Fig. 8.11.

Laser welding has been investigated for manufacturing automotive curtain airbags, which provide head protection from side impacts and during multiple rollovers (Fig. 8.12). Results showed leak versus pressure performance within the range achieved, using conventionally sealed seams.

Laser welding fabrics can lead to greater automation, increased productivity, and improved quality, offering manufacturers a competitive advantage and also reducing the incentive to relocate production to regions with low labor costs. Producing finished goods close to where they are sold also reduces shipping costs. In addition, the process can reduce noise levels and injuries in the workplace.

Further developments in material handling, clamping, and fabric selection promise even greater benefits in

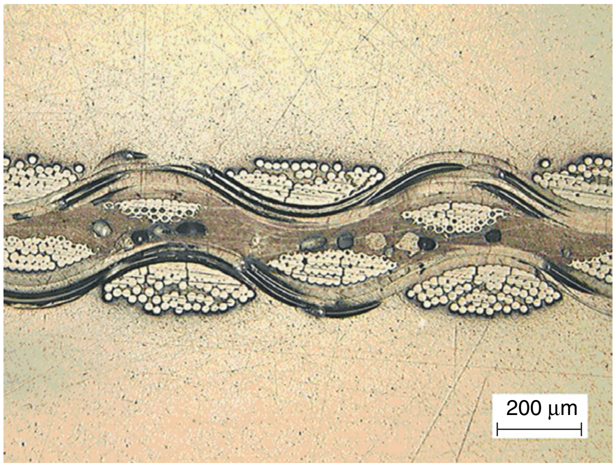

Figure 8.11. Microstructure of laser-welded nylon 6,6 fabrics, showing the horizontal melt line at the center and, above and below this, cross-sections through the warp, and weft fibers (Source: TWI Ltd).

Figure 8.12. Curtain airbag (Source: Autoliv).

terms of process speed, automation, and quality improvements. Laser welding is already being used successfully in some simple applications, and it is expected that increasingly complex articles will be manufactured using this technique.

8.4 Materials

8.4.1 Absorbers Used in Transmission Laser Welding

The most commonly used absorber in transmission laser welding is carbon black, where it is normally mixed as an additive into the polymer resin. Carbon absorbs relatively evenly over a wide region of the electromagnetic spectrum. When used as an absorber for welding, its color and absorption properties are unchanged by the process.

More recently, a wavelength selective absorber such as Clearweld has been used. It has very strong absorption for near IR, and can be matched to specific laser wavelengths, with much weaker absorption at visible wavelengths. It therefore has very little visible color. It is applied as a coating positioned at the joint interface, using liquid deposition techniques or as an additive in the polymer resin [4].

8.4.2 Laser Transmission Measurement of Plastics

It has already been stated that for transmission laser welding, it is preferable for the part closest to the laser to be more than 10% transmissive. It is therefore useful to measure the transmission of radiation through polymers, as a guide to their suitability for welding. The measurement is carried out using a calorimeter to measure a laser pulse energy directly and then with the test material between the sensor and the laser source. The pulse energy measured in these two cases is compared. A more detailed measurement includes the reflection of energy at the surface, which can be significant for some materials and which will also limit the energy available to the weld.

The spherulites in semicrystalline plastics and any particulate or fiber additives lead to the scattering of the laser beam. This leads to a reduction in beam intensity at the weld interface. Measurements can be used to indicate the size of such effects to allow the beam shape and process parameters to be controlled accordingly.

8.5 Equipment

8.5.1 Introduction

The main elements of a laser welding system are:

- Power supply, including a chiller for higher power laser sources
- Laser source
- Beam delivery optics (lens, mirror, or fiber based)
- Beam focusing or shaping optics, including masks, if required
- Beam manipulation optics, such as galvanometer controlled mirrors
- Workpiece clamping and support
- Workpiece manipulation

8.5.2 Laser Types

The main types of laser used for transmission laser welding are diode, Nd:YAG, and fiber lasers in the wavelength range 0.8 μm–1.1 μm. At longer IR wavelengths, CO_2, and other lasers with a wavelength in the region of 2.0 μm, may be used for direct welding (Table 8.2).

Nd:YAG: Nd:YAG lasers are widely used in industry for materials processing. High-power systems are

Table 8.2. Laser Types Used for Welding Plastics

	Nd:YAG	Diode	Fiber	CO_2	Ho:YAG or Tm:YAG
Wavelength (nm)	1064	780–980	1000–2100	10,600	~2000
Efficiency[a]	3	30	20	10	3
Approximate cost for 100 W system (US$k)	80	20	60	20	200+
Beam quality[b]	High	Low	High	High	High

[a] Efficiency is the percentage of the electrical power consumed by the laser that is emitted in the beam.

[b] Beam quality is the ability to focus the beam to a small spot size with a high energy density.

bulky, but lower-power systems are relatively compact. Water cooling is usually required. The beam is transferred from the laser to the workpiece via an optical fiber. It is feasible to combine the beam from more than one laser to produce higher powers if required. The high beam quality allows relatively small spot sizes to be produced.

Diode: Diode lasers produce radiation at a wavelength of 780–980 nm. Water cooling is usually required. Their relatively low beam quality means that they cannot be used to produce a spot size as small as Nd:YAG or fiber lasers. However, this is rarely a problem for plastics laser welding, where the relatively low purchase and running costs have attracted a great deal of interest. The beam may be delivered by an optical fiber, but the diode is sufficiently small and light that it is often feasible to use a direct system, in which the diode is included with a lens system in a single unit, typically around 150 × 150 × 300 mm (6 × 6 × 12 inches). This unit can readily be mounted on a gantry system or robot arm to manipulate the beam (Fig. 8.13).

Fiber: Rare-earth doped fiber lasers typically supply a wavelength in the range 1000–2100 nm. In the field of materials processing, much interest has been focused on wavelengths around 1100 nm to provide a direct replacement for Nd:YAG lasers, with equivalent beam quality, but greater efficiency. Systems are relatively compact and can be air-cooled. In the field of plastics welding, the use of fiber lasers has been demonstrated for a range of applications, including precision welding, films, textiles, and larger molded parts.

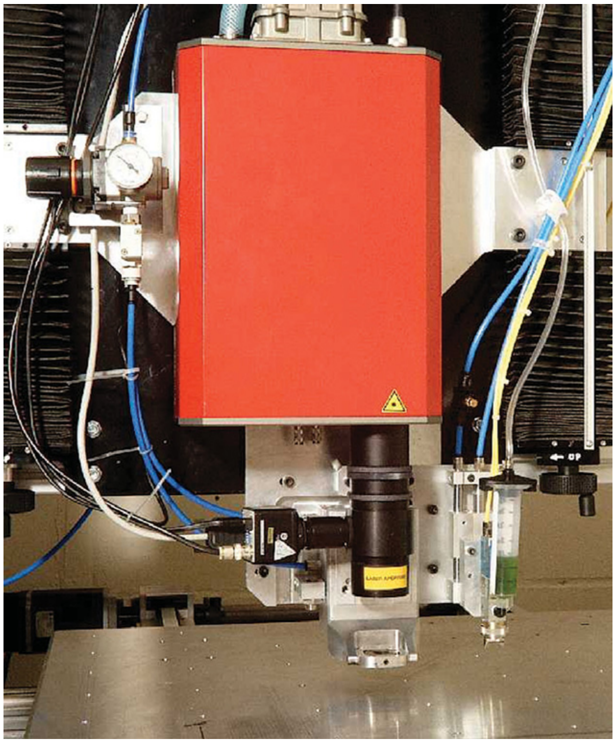

Figure 8.13. Diode laser mounted on gantry system (Source: TWI Ltd).

CO_2 Laser: CO_2 lasers are widely used in industry for cutting plastics. High-power systems are bulky with gas flow systems incorporated, but lower power systems are relatively compact. The beam is transferred from the laser to the workpiece via mirrors. Focused spot sizes of less than 200 µm (0.008 inches) are available.

2.0 µm Wavelength Lasers: YAG and fiber lasers that emit at a wavelength in the region of 2.0 µm are available. They are less commonly used than the other sources and are more expensive. The beam can be delivered down a fiber optic, usually has a good beam quality, and can provide small focused spot sizes.

8.5.3 Beam Delivery

The beam or workpiece manipulation equipment for laser welding will typically take one of the forms illustrated in Fig. 8.14, or a combination of one or more of these.

Moving Workpiece: With the laser fixed, the part can be manipulated to form a continuous weld. This can be achieved, for example, with rollers, or a single or two-axis moving table. This type of system is relatively simple to set up and program, but would not normally be used if three-dimensional (3D) welds are required.

Moving Laser: The optical system for a fiber-delivered laser or the laser head for a direct diode laser can be mounted on a variety of robotic systems. These range from simple two-axis gantry systems to multiple-axis robotic arms. The laser is manipulated around the part to be welded, potentially allowing complex, 3D welds to be produced. To facilitate automatic production, it is feasible to combine a moving laser with a moving part, for example by using a rotating table to present different faces of a component to a laser mounted on a robot arm.

Curtain Laser: The laser energy is spread into a line and then passed over the component, either by moving the laser or by moving the part. A mask is typically used to ensure that only the relevant areas of the component are exposed to the radiation. This is particularly suited for small components with a complex weld geometry. The process would usually be used only to produce two-dimensional welds. The welds may be completed very quickly with a single sweep of a line source.

Simultaneous Welding: If a large number of identical welds are required, then an array of diode lasers can be assembled in the shape of the weld to be produced.

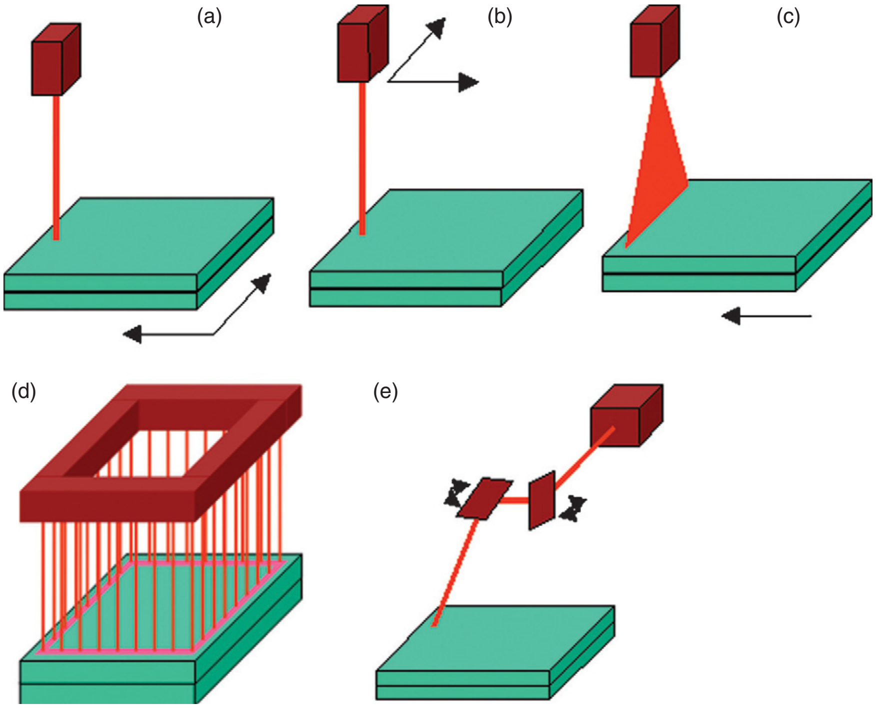

Figure 8.14. Laser welding methods: (a) moving workpiece, (b) moving laser, (c) curtain laser, (d) simultaneous welding, (e) scanning laser (Source: TWI Ltd).

This is then used to irradiate the whole joint simultaneously, with a typical cycle time of 1–3 seconds. This approach is well-suited to automated assembly. The equipment used is frequently based on ultrasonic welding equipment, and this process is typically used in place of ultrasonic welding where a good cosmetic appearance is required, or for components that are sensitive to vibration. Two- and three-dimensional welds can be produced. Since the entire joint is welded at the same time, this allows more collapse of the polymer at the joint and therefore wider part tolerances.

The methods for simultaneous welding include development of light guides, fed by fiber optic bundles, which are shaped to the item being welded. The light guide therefore provides both heating and clamping to the whole part at the same time [20].

Scanning Laser: The laser radiation is manipulated by a pair of orthogonal rotating mirrors over an area that may range from 50 × 50 mm (2 × 2 inches) up to approximately 1000 × 1000 mm (40 × 40 inches). In general, a larger working area implies a longer working distance and a larger spot size. It is possible to coordinate a number of scanning systems to give a larger working area. In general, only two-dimensional welds can be produced.

Repeatedly scanning the laser at high speed over the same path can be used to give quasi-simultaneous welding. As for simultaneous welding, this heats the entire joint area at the same time, allowing more collapse of the material in the joint and potentially allowing wider tolerances.

An alternative approach is to direct a scanning beam onto a mirror surrounding the weld line. This has been carried out using a cone shaped mirror surrounding a cylindrical part, allowing tube tips or small round components to be welded simultaneously.

8.5.4 Clamping

A wide variety of clamping systems have been used for transmission laser welding. They are mostly variants of the two systems illustrated in Fig. 8.15.

Variants of the fixed clamp include systems using mechanical fastenings, rather than an actuator, to apply a load. In the simplest variant, if the part design allows it, a bolt can be passed through the workpiece to apply the load. The transparent cover must be rigid enough to provide the clamping pressure. Thick acrylic or plain plate glass can be used. Borosilicate glass is less vulnerable to thermal shocks during welding, but more expensive. For welding of high-temperature polymers, quartz glass may be used. In all cases it is important to ensure that suitable safety precautions are taken to avoid the risk of injury if the transparent cover breaks while it is under load.

The moving clamp can use bearings, rollers, or a simple sliding shoe to apply a clamping load. Because the load is applied only at the point where the joint is irradiated, clamping loads may be much lower when a moving clamp is used. There is therefore less risk of distorting the workpiece, and equipment can be less

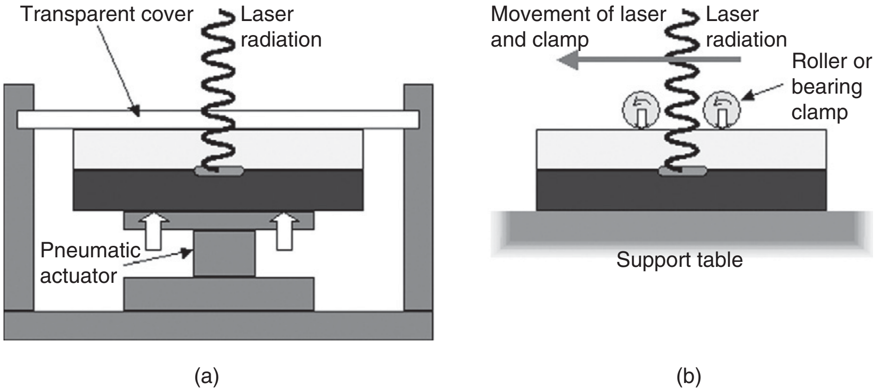

Figure 8.15. Clamping systems for transmission laser welding: (a) fixed clamp, (b) moving clamp (Source: TWI Ltd).

bulky. This is particularly advantageous for large components, where the application of a suitable clamping pressure to a large area can require large loads.

Welding in a nip between two rollers (Fig. 8.3a) is typically used to weld two flexible materials together, or a flexible film to a rigid base. The laser beam is directed toward the nip between the rollers and positioned to heat both internal surfaces of the joint just before they are pressed together. Very high speed processing (over 500 m/min; 1640 ft/min) has been demonstrated using this technique.

Another method of applying force at the point of heating, a variation of the moving clamp, is to transmit the laser beam through a ball-shaped transmissive clamp. The ball rolls in an air-bearing socket. The air flow also helps to keep it clean and maintain a consistent transmission of energy. Such a clamp has been used successfully with 3D robotic welding equipment for complex shaped parts.

8.5.5 Absorber Application Equipment

Carbon black is generally dispersed in the polymer. The liquid absorber coatings, such as Clearweld, can be applied using several methods. In essence, any method that can be used to apply a low-viscosity liquid to a substrate can be used. However, the critical requirements for applying these solvent-based materials include:

- Consistency—entire weld area contains a uniform concentration of absorber.
- Repeatability—every part has the same amount of absorber.
- Lack of contamination—little or no additives or contaminants to the material system.

The method of application is dependent upon the design of the parts to be coated, and the requirements of the end user. In general, a method of application should apply the liquid only to the area where a weld is desired. Precise application of the material eliminates the need for a mask, which is often required in traditional through transmission laser welding. Other factors, such as speed of operation will also affect the choice of application method. The main application methods are:

- Liquid dispensing via a needle
- Spraying
- Brushing
- Dipping
- Felt tip
- Dry film absorber of a compatible polymer to those being joined

8.5.6 Monitoring

Laser welding is unique in the precision with which the location and amount of energy applied can be controlled. To take advantage of this potential, a rapid and accurate monitoring method is required.

Monitoring may be applied for a number of reasons, both to confirm that various stages of the process have occurred and to assess the quality of the weld:

- Confirmation that the IR absorber is applied correctly to the parts before welding.
- Indication that the parts are in contact during the process.
- Indication that weld heating is being carried out and control of temperature.
- Indication that the parts are in contact after completion.
- Indication that the weld has been achieved after completion.
- Indication that the weld quality and strength are satisfactory.

Monitoring methods can give information for most of these points with varying degrees of confidence; however it must be noted that complete quality and weld strength assurance can only be achieved with destructive testing.

Monitoring of other polymer joining methods is generally carried out by monitoring process parameters, such as energy utilized, displacement, and so on. These can also be applied with laser welding, but the process is also well-suited to the use of optical methods such as IR thermography. This and other optical methods are summarized in Table 8.3 [21].

8.6 Joint Design

A selection of successful joint designs suitable for transmission laser welding is shown in Fig. 8.16. In general, it must be ensured that the energy reaching the joint interface is sufficient for melting the interface material without overheating the material on the outer surface and, as far as possible, is evenly distributed at the interface. Extra care may be required to ensure even distribution of energy for interfaces angled to the beam direction, or for complex-shaped parts that have different thicknesses along the joint line. Parts must be well fitting. A surface roughness less than 50 μm (0.002 inches) may be used as a general rule of thumb. Joints are often designed to be self-aligning, may incorporate a snap-fit to hold parts in place for welding, or can be sized to allow self clamping. As an example, tubes may be arranged to have an interference fit to allow self-clamping [22].

8.7 Welding Parameters

8.7.1 Main Parameters and Effects

As with all plastics welding processes, the three critical process parameters are temperature, time, and pressure. In laser welding these are controlled by laser

Table 8.3. Summary of the Features of the Optical Monitoring Methods

Monitoring Method	Suitable for	Advantages	Limitations	Availability
Visible light imaging	Viewing the weld during and after the welding process. For both absorber resin and coating methods with IR and carbon black absorbers.	Easy to set up and use. Indicates weld region where the two joint surfaces have merged.	Only suitable for transparent and translucent upper materials.	Off-the-shelf components.
IR thermography	Temperature measurement and heating control during the welding process. For IR and carbon black resin-based systems. Care needed in use with IR absorber coatings.	Provides rapid temperature reading of use in control of the laser power in real-time.	Difficult to use with low emissivity materials and where upper material transmission is poor.	Available at relatively low cost.
IR imaging	Verifying location of absorber coating before and after welding, showing where heating has occurred. Also gives image of heated zones just after welding.	Proven laboratory technique suitable for checking coatings on parts before welding and the extent of the weld afterwards.	Interference from the laser wavelength if used at the time of welding. Not useful for weld checking of absorber filled resins after welding.	Might also be used at the time of welding with further development.
Spectrometry	Measuring the coating absorption before and after the weld, and potentially during the weld. Verification of an intimate surface connection.	Checks position and concentration of the coating before welding and that remaining after welding.	Difficult method to use at the time of welding. Not useful for weld checking of absorber filled resins after welding.	Might also be used at the time of welding with further development.

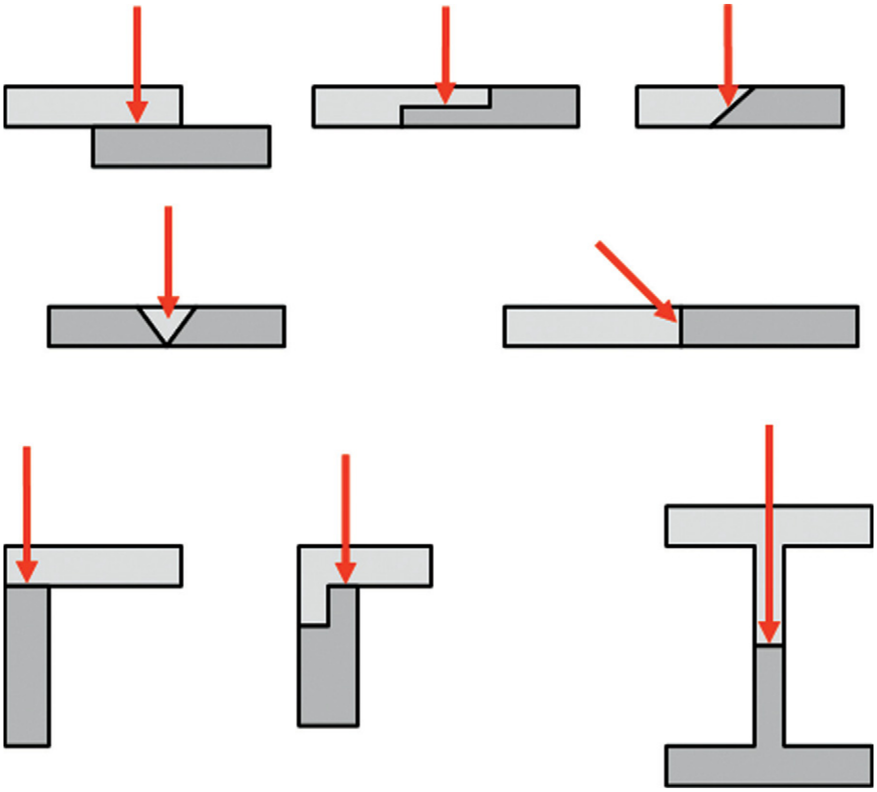

Figure 8.16. Potential families of joint designs (Source: TWI Ltd).

power, laser spot size, irradiation time (either fixed or moving systems), the presence of laser absorber materials, and clamping load.

The energy density used during welding combines the process parameters of temperature and time. It is determined by the laser power, the spot size at the joint, and the irradiation time (for fixed processes), or welding speed (for processes in which the part moves with respect to the laser):

$$\text{Energy density} = \frac{\text{Power} \times \text{Time}}{\text{Spot size}}$$

or

$$\text{Energy density} = \frac{\text{Power}}{\text{Spot width} \times \text{Speed}}$$

If the energy density is too low, then insufficient heating takes place and the material at the joint is not held at a high enough temperature for a sufficiently long time to form a strong weld. On the other hand, if the energy density is too high, then excess heating can degrade the polymer at the joint, resulting in porosity, or, in extreme cases, burning or charring of the polymer. Either case results in a weld of lower strength than the optimum. In practice, a relatively wide processing window can usually be found within which satisfactory welds can be produced. Typically laser welding applications use an energy density within the range 0.1–2 J/mm^2, although this will vary depending on the depth of melt required to ensure a satisfactory joint. Although the energy density can be used to characterize the welding process, it should be treated with caution. The conduction of heat away from the joint during welding means that using the same energy density will not necessarily result in the same quality of weld. For example, with a constant spot width, doubling the power will usually allow the speed to be more than doubled, whilst retaining the same performance from the weld.

The other factor affecting the amount of energy made available to the weld is the density and absorbance of the absorber present at the joint interface. A higher density of absorber will allow the weld to be made faster or with a lower power laser.

The pressure applied is controlled using the clamping system. If the workpieces are not clamped together during welding, or if the pressure at the joint is insufficient, then the joint faces will not be in intimate contact. This will result in poor conduction of heat to the

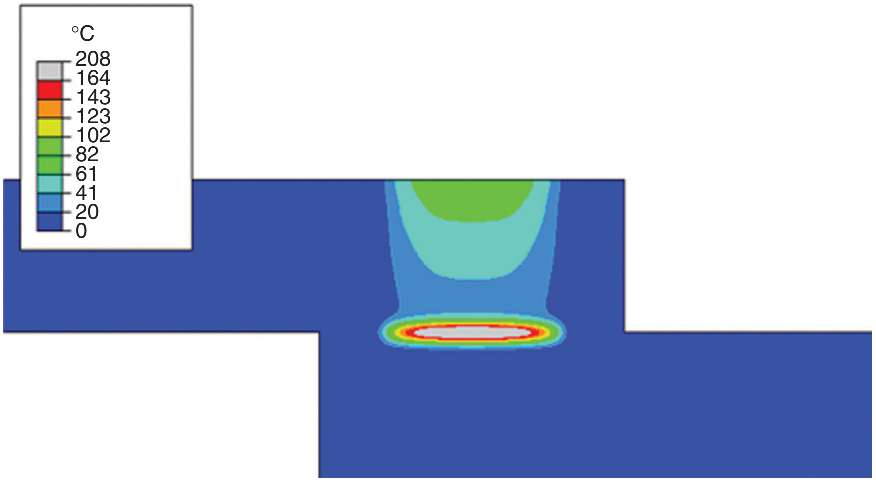

Figure 8.17. Typical temperature distribution for a laser-welded specimen resulting from finite element analysis (Source: TWI Ltd).

Table 8.4. Troubleshooting Guidelines for Laser Welding

Problem	Cause	Solution
Burning	Surface contamination, surface roughness, or contamination within the polymer	Clean surfaces at the seam and the surface through which the laser beam enters the polymer. Remove detrimental additives
	Laser-induced breakdown—the result of reaching a threshold energy density at which the material changes from being highly transmissive to highly absorptive	Reduce laser energy Eliminate air at the seam or at the surface where the beam enters: • apply film tape or other transmissive plastic (e.g., acrylic) over surface • blow inert gas across surface or weld interface
Surface melting	Surface contamination	Clean the surface
	Laser absorption or scattering at the surface—more likely to occur with semi-crystalline materials. At sufficient energy density, the laser beam scatters or is absorbed at the surface to cause melting	Reduce laser energy
Bubbling in the seam	Overheating	Reduce laser energy Reduce amount of absorber applied or use lower concentration
	Inadequate clamping pressure	Increase clamping pressure Ensure even pressure (evident if bubbling always occurs in the same location)
	Entrapped Moisture	Ensure polymers are dry prior to welding
Uneven weld	Uneven clamping pressure	Ensure even clamping pressure
	Uneven absorber layer	Examine application of material system
	Inadequate pressure	Increase pressure Increase laser energy
Poor weld strength	Inadequate laser energy	Increase laser energy Decrease weld speed Increase absorber concentration Increase pressure
	Low level of energy absorption	Increase amount of absorber applied Increase laser energy Decrease weld speed

(*Continued*)

Table 8.4. Troubleshooting Guidelines for Laser Welding (Continued)

Problem	Cause	Solution
	Low laser transmission through top substrate	Change polymer Increase amount of absorber applied
	Excessive level of energy absorption	Reduce amount of absorber applied
	Excessive pressure—thinning of textiles at the seam	Reduce pressure Reduce laser energy Increase weld speed
	Excessive laser energy	Reduce laser energy Increase weld speed Reduce pressure Reduce amount of absorber applied
	Incompatible polymers (dissimilar materials)	Use different materials
	Melting temperature difference too large	Use different materials
	Polymer/solvent compatibility—solvent used in absorber fluid system degrades polymer surface	Use absorber with different solvents
Residual color	Carbon black used as absorber	Use low-color IR absorber
	Excessive level of absorber for laser energy used	Reduce amount of absorber applied and increase laser energy

upper workpiece and limited interdiffusion of polymer chains across the joint interface.

Both effects result in a weld of lower strength than the optimum. Care is needed to ensure that a clamping load actually provides pressure at the joint. Typically, clamping pressure in the range of 0.1–1 N/mm^2 (14–145 psi) is used. If the workpieces bend under the clamping load in such a way that the joint is distorted, then a poor weld can result. For this reason, it is often useful to have some compliance, for example, an elastomeric element, in the clamping system.

8.7.2 Modeling

Thermal modeling of polymer welding is applied most easily when the process is predominantly one of diffusion at the surfaces and has minimal melt flow. Transmission laser welding is one such process. Models may be based on classical heat-flow equations for a specified joint design or using finite element methods (Fig. 8.17) [23–25].

8.8 Troubleshooting

The troubleshooting guidelines given in Table 8.4 summarize the appropriate diagnostics of common problems that might be encountered during laser welding of plastics.

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9 Infrared Welding

9.1 Process Description

Infrared (IR) radiation can be used as a noncontact heat source for welding of polymers. The IR radiation is often supplied by heated metal plates, which radiate at wavelengths between 1 and 15 µm (Fig. 9.1) or IR lamps, which radiate at wavelengths predominantly between 1 and 3 µm. This radiation can cause heating and melting when incident on a polymer surface. The IR source is removed after melting has occurred, and the parts are forged together and allowed to cool down.

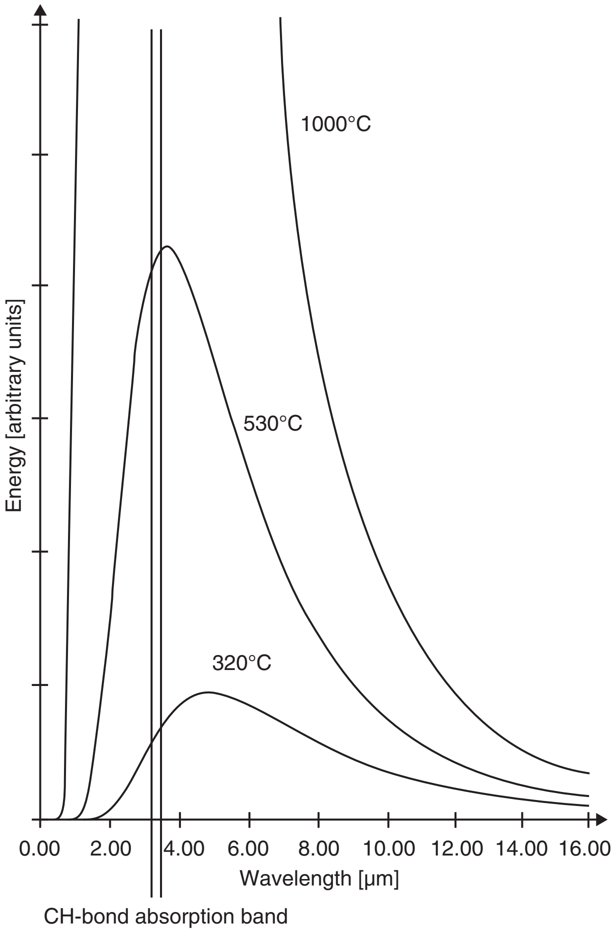

Figure 9.1. Absorption of radiation of an idealized black body as a function of wavelength. Absorption of IR radiation by C–H bonds occurs at wavelengths of 3.3–3.5 µm (Source: TWI Ltd).

9.1.1 *IR Interaction with Polymers*

When radiation is incident on a polymer surface it can be reflected, transmitted, or absorbed. It is the absorbed portion that leads to temperature increase and consequently leads to melting of the polymer. The amount of radiation absorbed by a pure unfilled thermoplastic is determined by the vibrations of its atoms. For a vibration to be IR-active, it must be associated with a change in dipole moment which can be activated by the oscillating electric field of incident IR radiation. Certain vibrational modes have frequencies within the IR spectrum and can therefore absorb IR radiation of specific wavelengths. While there are many different modes of vibration, two common modes are stretching and bending. Wavelengths of 3.3–3.5 µm correspond to vibrational modes of C–H bonds; alcohol, carboxylic acid, or amide groups absorb IR energy at wavelengths between 2 µm and 3 µm. The absorption spectra of some polymers are shown in Figs. 9.2–9.4.

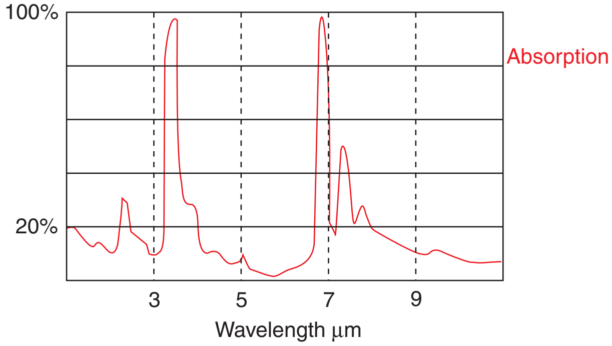

Figure 9.2. IR absorption of 0.1 mm (0.0039 inches) thick polyethylene (Source: Heraeus Noblelight).

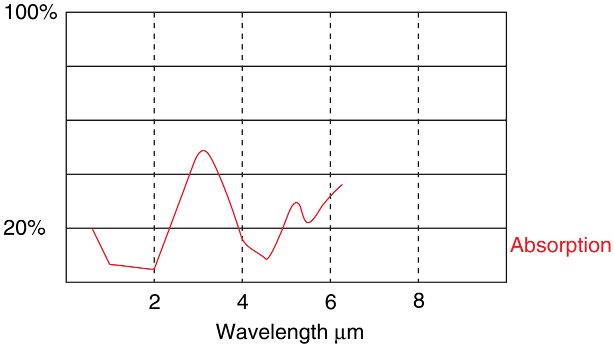

Figure 9.3. IR absorption of 0.02 mm (0.0008 inches) thick PVC (Source: Heraeus Noblelight).

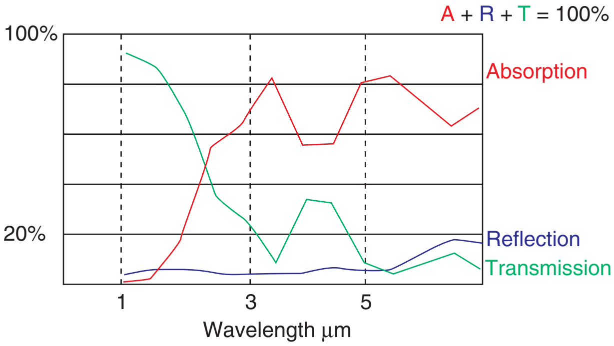

Figure 9.4. IR properties of 5 mm (0.197 inches) thick clear Perspex (Source: Heraeus Noblelight).

As can be seen from the above-mentioned figures, different polymers have maximum absorption at different IR wavelengths. Therefore, the choice of IR source (with specific wavelength distribution) is crucial to achieve an efficient melt and a satisfactory joint.

9.1.2 Process Types

There are two basic types of IR welding: surface heating or noncontact hot plate welding, and through-transmission IR (TTIR) welding.

9.1.2.1 Surface Heating

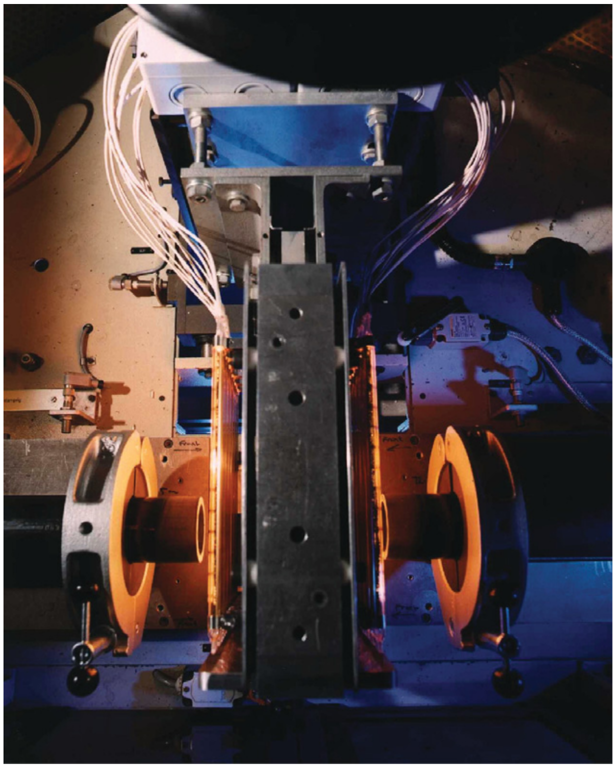

Figure 9.5. IR lamp welding of plastics pipes (Source: Heraeus Noblelight).

This can be achieved by using an electrically heated metal plate or IR lamps. The metal plate, which in some cases is coated with a ceramic, is heated to a temperature between 310°C (590°F) and 510°C (950°F) depending on the thermoplastic to be welded and the size of the welding machine. For IR lamp welding, the standard heater plate is replaced with two banks of short-wave IR emitters clamped and spring-loaded on either side of a movable platen (Fig. 9.5). Powers can be significantly greater compared with conventional hot plate welding, and weld times are significantly shorter. Since short-wave IR radiation (0.78–1.4 µm) can penetrate deeper into a polymer, this minimizes the thermal damage to the surface. This technique is also capable of handling large surface area products, as it is a simple operation to add more emitters to the heating bank.

In both cases, the process is similar to heated tool or hot plate welding and consists of three phases, as shown schematically in Fig. 9.6. In Phase I, joint surfaces of the parts to be welded are held at a specified distance from the heat source, and are heated to the melt temperature of the plastic. When a molten layer of a desired thickness is obtained, the radiant source is removed, and the parts are brought together under pressure. Phase II is the changeover phase which is the elapsed time from removal of the heat source to contact of the parts. This phase should be as short as possible in order to reduce surface cooling. Pressure is applied until the joint cools and solidifies during Phase III, to achieve intimate contact between the parts. Molecular diffusion across the joint interface during this phase determines joint strength. In some equipment, forced cooling is used to reduce the cooling time [1].

For more practical details the three phases can be divided into six steps as follows:

(1) *Loading Parts*: The parts are usually loaded to the fixture; some fixtures have a vacuum to assist with securing the parts.

(2) *Press Actuation*: The operator does this usually by closing two palm buttons and the IR source is translated between the two parts to be welded.

(3) *IR Application*: Once the IR source and the parts are securely located, the IR radiation is applied to the parts. This initiates heating and melting of the faying surfaces.

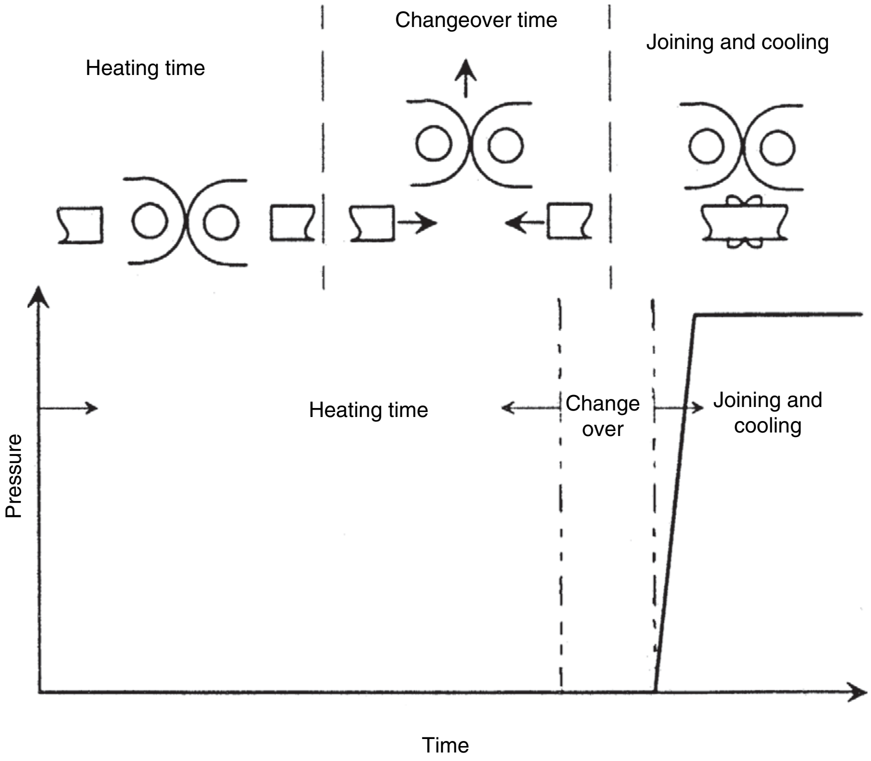

Figure 9.6. Schematic of IR welding process as well as a pressure–time curve, showing the three phases of infrared welding (Source: Ref. [7]).

(4) *Changeover*: After the IR energy is applied to the parts, the source is translated out of the way and the parts are brought into intimate contact.

(5) *Clamp/Hold*: The parts are held together under a preset pressure to increase intimate contact and subsequently facilitate molecular diffusion as well as squeezing out any contamination from the weld zone. There are usually mechanical stops used to restrict the movement of the parts and excessive melt displacement. If such stoppers are not used, it is possible for all of the melt to be squeezed out of the weld zone resulting in a poor weld often referred to as "cold-joint".

(6) *Unloading*: Once the molten material is sufficiently solidified, the parts are removed.

Table 9.1 shows typical cycle-times required for each of the steps mentioned above.

In some cases, particularly when the parts to be joined have large and complex geometry, heated gas is forced into the gap between the work pieces, achieving more uniform heating over the faying surfaces [2].

9.1.2.2 Through-transmission IR Welding

This method is based on the IR energy passing through one of the components to be welded and being absorbed by the second component at the interface where the heat generated melts the transparent polymer, as illustrated in Fig. 9.7.

Table 9.1. Typical Surface Heating IR Welding Cycle

Steps	Typical time (sec)
Loading parts	3–15
Press actuation	1–2
IR radiation application	1–5
Changeover	1–2
Hold phase	1–3
Unloading	5–10

TTIR welding can be conducted either by joining a transparent structure to an opaque one, or by using a thin interlayer absorbing film between the two layers to be joined. Usually, only low forces are applied to the layers to keep them in contact and allow heat transfer and air blowing over the upper layer can both cool and apply the weld force. Using filter media can help remove unwanted wavelengths from the IR source [3].

Nearly all polymers are "transparent" to IR energy in the near-IR part of the spectrum; even polymers that are opaque to visible light can be welded using this method.

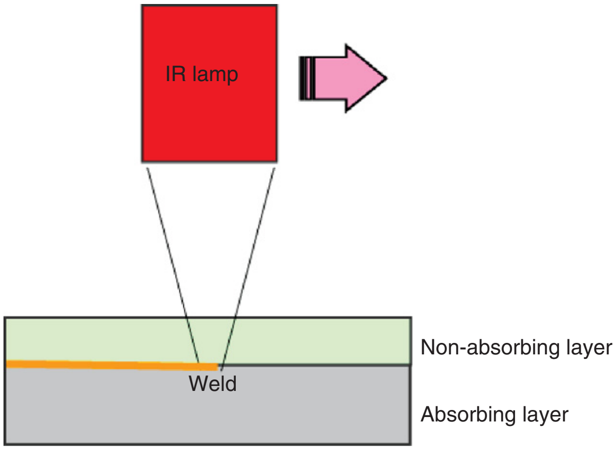

Figure 9.7. Schematic of TTIR welding (Source: TWI Ltd).

Some advantages of TTIR welding over the surface heating method include:

- It is a preassembled method, and for many applications, this is critical to allow subcomponents to be held in place during the welding process without complex fixtures.
- Speed and flexibility, with cycle times of 3–5 seconds.
- Even unsupported internal walls with complex curvature can be welded, as long as the optical properties of the material allow illumination of the faying surfaces. Applications of this type will be difficult with other processes known for relatively fast cycle times such as vibration welding.
- One of the most important advantages is the weld quality, leading to parts with excellent aesthetics.
- There are no large heated platens, and only the weld area is heated.

However, with TTIR welding, one of the components has to be transparent. Also, crystalline polymers such as PP and PE tend to promote internal scattering of the radiation, which limits the thickness of the clear part to 3–5 mm (0.12–0.20 inches). The other part also needs to be absorbent, and this is usually achieved by the addition of carbon black or another IR-absorbing dye to the interface.

The welding process consists of five steps:

(1) *Loading Parts*: This involves manually placing the parts into the fixture; often there is only one fixture (the lower fixture) that holds both parts.

(2) *Press Actuation*: Initiated by the operator and is achieved by the closing of two palm buttons.

(3) *IR Application*: Once the parts and the IR source are properly located, the IR radiation is applied to the parts. This promotes melting and welding of the faying surfaces.

(4) *Clamp Phase*: The parts are held together under a preset pressure to ensure intimate contact between the molten surfaces.

(5) *Unloading*: Once the molten material is sufficiently solidified, the parts are removed.

Typical cycle times for TTIR welding are presented in Table 9.2.

9.2 Advantages and Disadvantages

IR welding is a fast and economical method for joining plastics. IR radiation can heat a polymer and create a melt zone very quickly. Parts can therefore be welded at least 30% faster than in heated tool welding. Also, the fact that heating is achieved without physical contact eliminates any problems of material sticking to the hot plate or wear of the hot plate coating as in heated tool welding, and contamination of the joint interface is minimized. IR welding is able to weld low-modulus materials, such as thermoplastic elastomers, since there is little or no shear of the weld piece during heating. Also, due to limited displaced material compared to heated tool welding, the weld beads are smaller, increasing the flow in pipes and reducing the risk of micro-contamination at the beads [1, 4–9].

However, IR welding is not suitable for clear materials unless an absorbing material is used at the interface. In addition, parts must be molded very precisely as there is no contact-based melt stop to flatten/parallel

Table 9.2. Typical TTIR Welding Cycle

Steps	Typical time (sec)
Loading parts	3–10
Press actuation	1–2
IR radiation application	1–10
Hold phase	1–3
Part unloading	5–10

joint surfaces. In addition to the wavelength of the IR source, the depth of penetration of IR radiation depends on many factors, including the polymer's absorption characteristics, which could vary strongly with minor changes in polymer formulation. Therefore, consistent IR welding requires close attention to be paid to batch-to-batch polymer uniformity.

9.3 Applications

Since the early 1990s, surface heating IR welding has been used for the joining of plastic pipes. More recently, TTIR welding has been investigated for this application. Other applications include welding of unplasticized PVC (UPVC) window frames, biomedical products where high production rates of welded seals are often required in flexible materials, and in the fabrication of laminates. In addition, IR welding has been used to manufacture parts from thermoplastic composites, where the process is able to achieve high energy densities over large areas [1, 4, 10, 11].

9.4 Materials

Optimum values for processing parameters and weld strength are dependent on properties of the materials being welded, especially on the manner in which the polymer absorbs IR radiation. Colorants or pigments added to a polymer alter the absorption properties, and optimal parameter values may change. Black colorant added to plastic dramatically reduces the amount of radiation transmitted through the material, so that almost all the radiation not reflected is absorbed at the surface. As a result, high surface temperatures are obtained at short heating times, extensive polymer degradation can occur at short heating times, and weld strength is lower than in noncolored materials. Black plastics are subjected to more thermal stress and smaller heat gradients. Noncolored polymers are more transparent, so that radiation absorbed at and below the surface heats and melts the joint area; thick molten layers form, and polymer degradation is minimal even at longer heating times [4, 8, 12].

IR welding is particularly useful for polymers with higher melting points, since it is a noncontacting process and therefore avoids stringing and/or joint contamination which may occur in contact hot plate welding techniques.

Some of the materials that can be joined using different IR welding methods are listed in Table 9.3.

Table 9.3. Typical Materials Compatibility with Through-transmission and Surface Heating IR Welding

Materials	Through-transmission	Surface Heating
PC	Good	Good
Acrylic	Good	Good
PS	Good	Good
ABS	Transparent grade only	Good
PVC	Transparent grade only	Good
PE	Thickness <5 mm	Good
PP	Thickness <5 mm	Good
PK	Thickness <5 mm	Fair
Elastomers	Thickness <5 mm	Fair
PA	Thickness <5 mm	Fair
Acetal	Thickness <5 mm	Fair
PTFE	Thickness <5 mm	Poor

9.5 Equipment

Radiant heaters or lamps used in IR welding include quartz-halogen, tungsten, nickel-chromium (Ni-Cr), or ceramic-coated heating elements. Ceramic-coated heating elements are used for lower temperatures and can produce joint surface temperatures of 320–530ºC (608–986°F) at a heating distance of 1.5–2.0 mm (0.06–0.08 inches). Quartz and halogen radiators are used for higher temperatures, 1000–3000ºC (1832–5432°F) and maximum emission occurs at wavelengths of 0.9–1.0 μm. Tungsten filaments produce intense radiation; however, they are only available in linear and spot shapes and are sensitive to pigmentation and formulation of the materials being welded. Ni–Cr heaters are available in different shapes, such as tubular, and can reach a temperature of 850ºC (1562°F) in minutes, radiating at 2–5 μm wavelengths. Reflective backings can be used to focus IR radiation for heating long and narrow regions in one plane or to disperse radiation for uniform heating of large areas.

Rigid clamping devices hold parts and heaters in place, preventing distortion and misalignment during the welding process, and pneumatic actuators can be used to move heaters and parts as necessary during welding. Microprocessor-controlled equipment allows control of processing parameters and data acquisition for quality control. Other features include melt and press-depth controls, noncontact sensors, power-operated loading doors, precision bearings and slides, and automatic feeding and ejection of parts. Hot tool welding equipment is commonly adapted for use in IR welding. IR welding machines for plastics pipes are shown in Fig. 9.8 and a machine for IR welding molded parts is shown in Fig. 9.9.

Figure 9.8. IR welding machines for plastics pipes (Source: Georg Fischer Piping Systems).

9.6 Joint Design

Varieties of joint designs are possible when using IR welding (Fig. 9.10). Material displacement is typically 0.030 inches (0.76 mm) that results only from 0.015 inches (0.38 mm) material displacement per side from material fusion during the weld/seal step as there is no displacement during the IR melt step. This may vary depending on material and geometry.

9.7 Welding Parameters

The main processing parameters in IR surface heating welding are:

- heating time
- distance between the parts being welded and the radiant heat source (heating distance)
- time required for the changeover phase
- welding pressure after removal of the heat source

Heating temperature depends on the melt temperature of the plastic and the geometry of the welding assembly (part dimensions, heating distances). In diffusion radiators without reflectors, radiation intensity decreases as heating distance increases. Decreased radiation intensity results in slower temperature increases and smaller temperature gradients in the weld zone and

Figure 9.9. IR welding machine for molded parts (Source: Forward Technology).

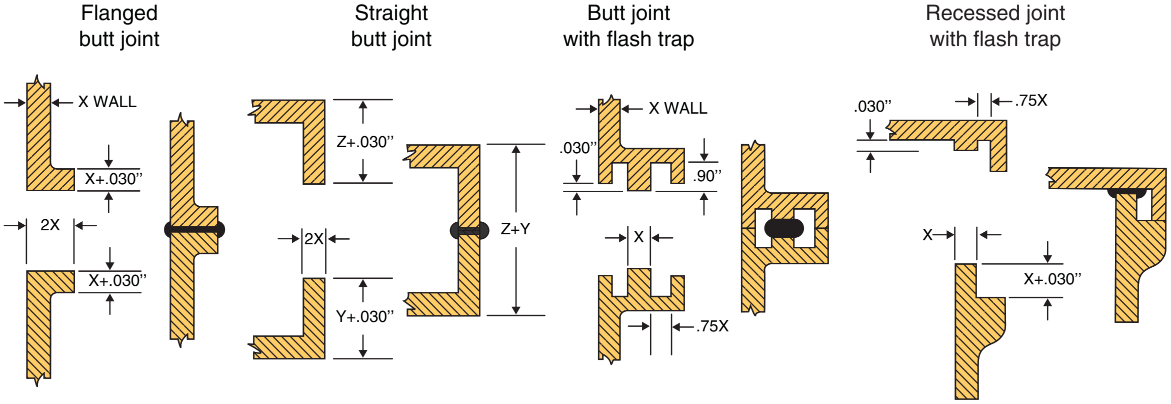

Figure 9.10. Some joint geometries for IR welding (Source: Forward Technology).

reduced thermal stress; however, longer heating times are necessary to achieve a particular melt thickness. Thickness and properties of the melt layer are important determinants of joint strength. Melt thickness is dependent on the amount of radiation reaching the weld interface and is influenced by heating time, heating temperature, heat source, geometry of the welding assembly, and characteristics of the polymers being welded.

Rapid increases in surface temperature can cause surface decomposition of the polymer. However, as melt thickness increases, accumulated decomposition products can be pushed out of the joint, increasing joint strength.

Increasing the heating distance requires substantial increases in heating time to achieve the same joint strength. Increased welding pressure generally increases weld strength due to squeezing out of decomposed material, until an optimum is reached. Further pressure increases result in decreased molten layer thickness and weld strength. Other factors affecting the weld quality are:

- dimensional stability of the parts
- polymer uniformity
- polymer color/translucency
- mold release agents
- dissimilar materials
- fillers
- moisture presence
- transition time between melt and weld steps

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10 Resistive Implant Welding

10.1 Process Description

In resistive implant welding, which was originally developed for high performance thermoplastics reinforced with continuous carbon fibers, current is applied to a conductive heating element, or implant, placed at the joint interface of the parts being welded. Electrical resistive (Ohmic) heating raises the temperature of the implant causing the surrounding plastic to melt and flow together, forming a weld.

The resistive implant welding process can be divided into three stages (Fig. 10.1).

10.1.1 Assembly

The heating element (implant) comprises the innermost portion of the weld stack and may take the form of carbon fiber prepegs, woven graphite fabric, stainless steel foil or wires, or braids or mesh made from copper or nickel alloys. Stainless steel heating elements can be used alone in welding thermoplastics. For welding thermosets or metals, the implants are impregnated with a thermoplastic, or are sandwiched between two thermoplastic layers. Carbon fiber prepegs are reinforced plastics usually composed of unidirectional carbon fibers in a thermoplastic matrix. Stainless steel heating elements introduce foreign material into the joint, but they are used to minimize any potential for galvanic corrosion, and to reduce fiber motion which has a detrimental effect on joint strength. The choice of the implant is based on cost, geometry, flexibility, and electrical resistance per unit length. The design of the implant is important, particularly the spacing of the wires, to ensure that molten polymer can flow between them during welding [1–8].

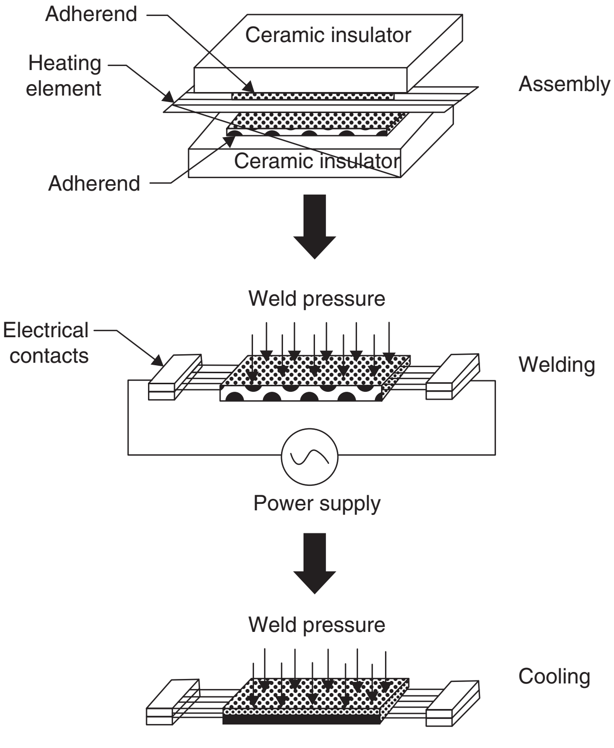

Figure 10.1. The resistive implant welding process.

The heating element is sandwiched between the parts to be joined, referred to as the adherends. For thermosets, composites, and metals, the adherend and the heating element are separated by an interlayer composed partly or entirely of a thermoplastic material. Thermoplastic materials used include neat thermoplastics or composites such as carbon fibers in a thermoplastic matrix. An interlayer thermoplastic material melts or softens below the melting point of the adherend, so that adherend degradation is minimized and mechanical performance of the joint is maintained. Insulators on the outermost ends of the weld stack complete the assembly.

10.1.2 Welding

To begin the welding cycle, pressure is applied to the weld stack, and electric current is passed through the implant. Resistive heating of the implant causes a rise in temperature; the adjoining thermoplastic material melts (for semicrystalline thermoplastics) or softens (for amorphous thermoplastics) and flows under pressure. Any surface irregularities are smoothed out, and molten plastic is squeezed out of the weld interface, removing any interlaminar voids.

10.1.3 Cooling

After a set time, the power is turned off, allowing cooling and solidification of the weld under pressure.

10.2 Advantages and Disadvantages

Resistive implant welding is simple to control and process cycle-times are short (30 seconds to several minutes). It is not restricted to flat surfaces, as in vibration or hot plate welding. Because the heating element remains in the joint after welding, repair of poor quality joints is possible, and joints can be disassembled to aid the recycling of individual parts.

Resistive implant welding can be used to join dissimilar materials, such as thermosets and metals, which would otherwise be joined by traditional techniques using thermosetting adhesives or mechanical fasteners. Due to the fusion bonding of the thermoplastic material, the weld displays a higher mechanical performance and provides barriers to moisture and solvents, leading to long-term durability.

A disadvantage of the technique is the possibility of current leakage away from the implant, causing uneven heating and potential for variation in the mechanical properties of the weld. In addition, since the implant remains in the joint, it can act as a void, affecting local mechanical stress distribution [3–9].

10.3 Applications

The use of resistive implant welding is growing in the aerospace sector for the joining of lightweight thermoplastic composites based on polyetheretherketone (PEEK), polyphenylene sulfide (PPS), and polyetherimide (PEI). Applications include secondary and tertiary load-bearing components such as ribs and spars. The technique has also been employed by the marine sector for dinghy hulls and the automotive sector for two-part car bumpers.

However, the biggest application area is probably the electrofusion technique for joining thermoplastic pipes such as PE (see Section 10.7).

10.4 Materials

Almost any thermoplastic can be joined by resistive implant welding and the technique can also be used to weld dissimilar materials, including thermoplastics, thermoplastic composites, thermosets, and metals in many combinations using a thermoplastic interlayer. The joint strengths of thermoplastics and thermosets are higher using this welding method than those obtained using adhesive bonding [6].

Accurate control of heating and cooling rates is important when welding some plastics, especially semicrystalline thermoplastics. Optimal processing parameters are needed to achieve reproducible bond uniformity and high joint strength [7, 8].

10.5 Equipment

Besides the implants themselves, equipment for resistive implant welding consists of a power supply and press system. Power supplies can either be the constant current or constant voltage type. Constant current supplies are preferred because they have the least variation in power delivered to the implant. Any variation in resistance of the connections, leads, or implant is dealt with by automatically adjusting the voltage to drive the demanded current. However, these are costlier and the constant voltage type power supplies are more widespread in industry.

Resistive implant welding machines can be automated or operated manually; pneumatic cylinders are used to apply pressure during the welding cycle.

10.6 Welding Parameters

Welding parameters for resistive implant welding are power or current applied to the heating element, pressure, temperature, dwell time (time held at the peak temperature or current), and cool time. Since the melt flow of the polymer is a function of the molecular weight and the temperature, the pressure is often determined experimentally before full-scale production. A three-stage welding cycle is normally used: a ramp up stage, a peak current stage, and a ramp down stage. Weld cycle times are about one minute [5, 7, 8].

The resistive implant welding process can be performed at either constant power or constant temperature. In constant power processing, a particular voltage and current is set for the entire weld, and welding occurs for a specified time. This process is not isothermal, and peak temperatures are difficult to predict. In constant temperature resistive implant welding, thermocouples are used to monitor the welding process to adjust current and voltage as necessary. The constant temperature process provides more thermal uniformity, but is not used commonly [5].

Resistive implant welding of large-scale components (greater than coupon-size) requires substantial load and power levels. One modification of the resistance welding process for large parts breaks the bond-line into segments, which are then heated sequentially. Heating large components simultaneously can result in overheating at the part ends due to surface anomalies and a nonuniform pressure distribution during the welding process. Process adaptations such as low power levels and more rigid tooling can reduce overheating and produce better bond quality [6].

10.7 Electrofusion Welding

10.7.1 Process Description

The electrofusion technique is mainly used for welding pipes made from PE for the conveyance of gas, water, and effluent. It is also used in industrial applications for joining pipes made of PP and PVDF, and more recently it has been used for welding nylon gas pipes [10].

The process involves the use of a molded socket fitting containing two electrical resistive heating coils separated by central cold zones (Fig. 10.2).

The prepared pipe ends are inserted into the sockets, clamped, and an electric current is passed through the coils for a preset time. Heating of the coils and surrounding polymer, and heat transfer to the pipe wall takes place. Cold zones at the ends of the fitting contain the melt within the fusion zones, allowing a high melt pressure to develop and formation of a homogeneous joint (Fig. 10.3).

Joint formation in electrofusion welding consists of four stages. In the incubation stage (I), a current is passed through the coils; the surrounding material in the coupler heats and expands, filling the gap between the pipe and coupler. Contact of the coupler with the pipe then heats the pipe material. In the joint formation stage (II), melt from the coupler combines with that from the pipe, and a stable melt pool is created. Molten material is prevented from extruding out of the joint by cold zones in the coupler, and the low thermal conductivity of the plastic restricts resin melting to the fusion zones. The strength of the weld at this stage is low, producing brittle failures due to limited intermolecular diffusion across the weld interface. Higher molecular weight molecules begin to diffuse across the weld interface in the joint consolidation stage (III), where the joint strength increases with increasing heating or fusion time, and the failure mode in strength tests changes from brittle to ductile. Excessive fusion times, however can result in polymer degradation. Current is terminated in the joint cooling stage (IV), and the weld starts to cool with the pipe still clamped to prevent movement. As cooling continues, the polymer recrystallizes, beginning from the areas adjacent to the cold zones, and then proceeds inward toward the centers of the fusion zones.

Pipe preparation is essential for successful welding. The pipe ends to be joined must be thoroughly scraped to remove the invisible surface layer of oxidized material (caused by UV exposure) which would otherwise inhibit molecular mixing and good fusion. For small diameter pipes, simple hand scrapers are used, whilst for larger sizes, a rotary mechanical scraper can be used (Fig. 10.4), which saves effort and renders a uniform finish.

Typically a layer in the range 0.2–0.4 mm (0.008–0.016 inches) must be removed. Contamination such as dust, grit, grease, or water must also be absent from the prepared surfaces. Some PE pipe manufacturers now produce pipe with an outer layer that can be peeled off, which negates the need for scraping. The layer can be

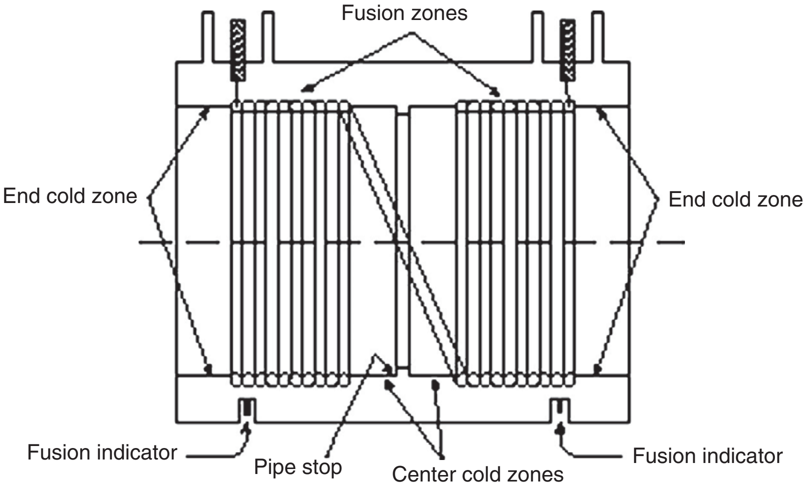

Figure 10.2. Schematic of an electrofusion coupler (Source: TWI Ltd).

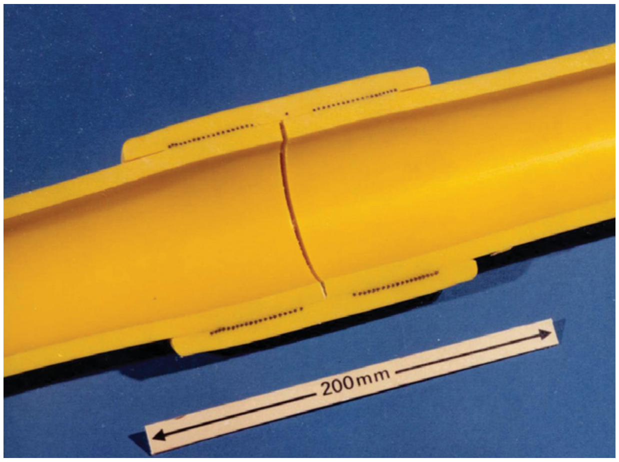

Figure 10.3. Photograph of a cross-section of an electrofusion joint (Source: TWI Ltd).

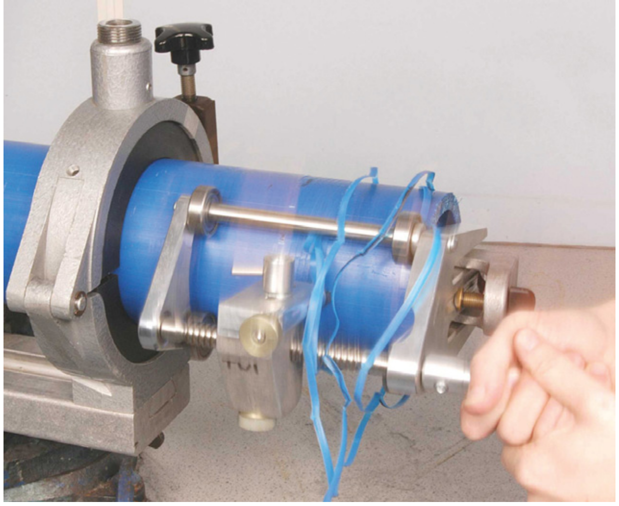

Figure 10.4. Mechanical scraping of pipe end (Source: TWI Ltd).

removed easily and quickly, revealing a clean surface layer, undamaged by UV, prior to insertion into the coupler sockets [11].

Pipe ends must be cut square and inserted into the coupler so that they reach the center pipe stop. This placement ensures proper functioning of the coupler cold zones and also ensures that all the heating wires are covered. The pipe to be joined must also be securely clamped throughout all stages of welding and cooling to prevent pull-out [12].

Electrofusion socket fittings can take the form of couplers, elbows, tees, and reducer, and are available across a range of pipe sizes of 16–710 mm (0.63–28 inches) for pressure pipes and up to 1800 mm (71 inches) for nonpressure applications. Connection of smaller diameter service pipes to larger diameter mains pipes are made using saddle fittings, typically branching saddles or tapping tees (Fig. 10.5) [13].

10.7.2 Advantages and Disadvantages

Electrofusion welding is a simple process that permits joining of preassembled pipes and fittings to be carried out quickly and with minimum equipment. It is easy to use for repairs, such as joining a replaced section of damaged pipe, and can be used where space is limited, such as welding pipes in a trench (Fig. 10.6). Electrofusion can also be used to join pipes of different wall thicknesses and different grades of material, for example, HDPE to MDPE (where permitted under local codes of practice) [14, 15].

A disadvantage of electrofusion is that it is susceptible to contamination, requiring careful handling of the pipe ends prior to insertion. This can be difficult to achieve whilst working in a muddy trench. Also, the fittings are consumables, so projects involving large diameter pipe and many joints can be become costly.

A further drawback of electrofusion is the difficulty in inspecting joints after they have been welded, since the weld is totally concealed within the fitting.

10.7.3 Equipment

There are three main items of equipment necessary for undertaking electrofusion welding: the fitting itself,

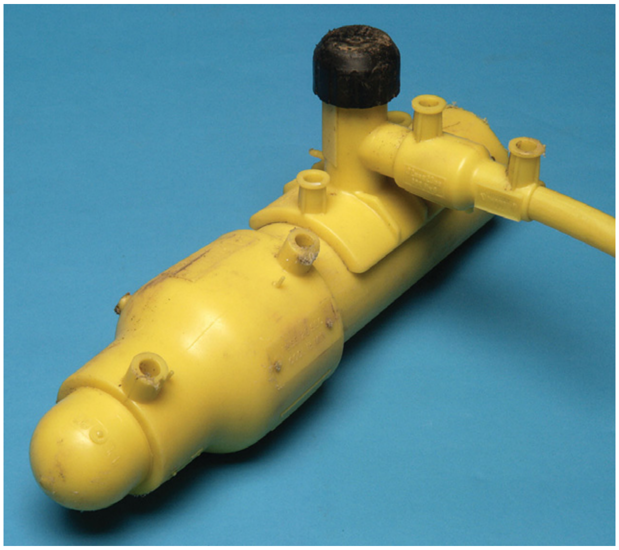

Figure 10.5. Electrofusion assembly showing tapping tee, reducer and end-cap fittings (Source: TWI Ltd).

Figure 10.6. Electrofusion welded joints in a trench (Source: TWI Ltd).

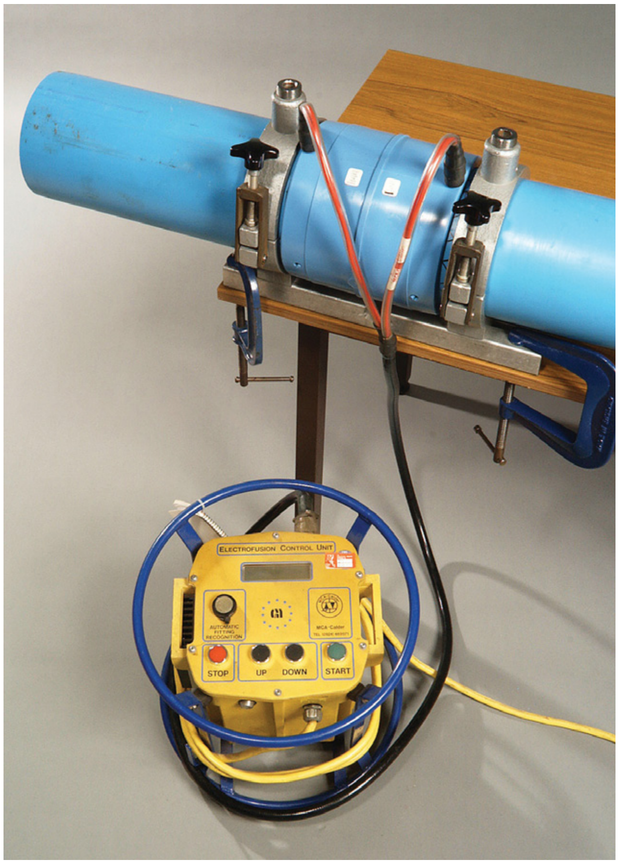

Figure 10.7. Electrofusion control unit connected to a fitting (Source: TWI Ltd).

Figure 10.8. Pop-up melt indicators (Source: TWI Ltd).

the electrofusion control unit (ECU) and the pipe restraining clamps (Fig. 10.7).

Couplers and other fittings for electrofusion welding are normally injection-molded. Larger diameter couplers are sometimes machined from thick wall pipe or billets. There are various patented methods of inserting the resistance wire into the fitting, often using robotic or CNC manufacture.

A feature of electrofusion fittings is pop-out melt indicators (Fig. 10.8). Expansion of the molten pool in the fusion zone causes these to activate during the welding cycle, signaling to the operator that melt pressure has developed.

The ECU supplies the necessary electrical current to the electrofusion fitting to energize and heat the coils. It takes power from either a mobile generator (typically nominal output of 110 V, 3.5 kVA rating), or from a standard mains supply, and converts it to the necessary voltage for the fitting.

There are many different types of ECU available on the market from a range of suppliers. Most of the latest models feature data storage facilities, where all the welding parameters of every joint, including date and time of day, are recorded on a memory chip for QA purposes. Other features such as a choice of manual or automatic operating mode, and a choice of operating language are usually available. A more recent development has been the introduction of a battery-powered ECU, suitable for making a limited number of joints in pipe sizes up to 63 mm (2.5 inches). The requirement for an auxiliary power source is eliminated, giving total freedom of use when welding on site.

10.7.4 Welding Parameters

The principal welding parameters for electrofusion are fusion time and cool time. The operating voltage is also a parameter but is usually fixed for a particular manufacturer's range of fittings, that is, they are all designed to work with the same supply voltage. Each size of electrofusion product has its own specific welding parameters. Table 10.1 shows how the fusion and cooling times increase with pipe diameter.

The same size fittings from different manufacturers sometimes have different fusion and cooling times. This is due to different design specifications, for example, differences in wire material and diameter, coil pitch, wire burial depth.

The welding parameters are normally displayed on the product, either by an adhesive label, or embossed directly onto the plastic. Many fittings also have the fusion data provided on a bar code tag which is read by a light pen connected to the control unit (Fig. 10.9).

Table 10.1. Typical Electrofusion Welding Parameters

Pipe Diameter (mm)	Fusion Time (sec)	Cool Time (min)
25	32	4
90	120	9
180	260	18
315	760	30

Figure 10.9. Electrofusion coupler showing embossed data and bar code (Source: TWI Ltd).

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11 Induction Welding

11.1 Process Description

Induction welding, also called electromagnetic or EMA welding, uses induction heating from radio frequency (typically 2–10 MHz) alternating current to magnetically excite an implant placed at the joint interface of the two parts being welded. This implant, or gasket, is normally a composite of the polymer to be welded with either metal fibers or ferromagnetic particles. The heat generated melts and fuses the implant with the surrounding material. It is a reliable and rapid technique, ranging from fractions of a second for small parts to 30–60 seconds for parts with long (400 cm; 157 inches) joint lines, and results in structural, hermetic, or high-pressure welds [1, 2].

The two most commonly encountered mechanisms by which heat can be generated by an induction field are eddy current heating and heating due to hysteresis losses. In eddy current heating, a copper induction coil (work coil), which is connected to a high-frequency power supply, is placed in close proximity to the joint (Fig. 11.1). As electric current at a high frequency passes through the work coil, a dynamic magnetic field is generated whose flux links the implant. Electric currents are induced in the implant, and when these are sufficiently high to heat the conducting material, the surrounding thermoplastic parts soften and melt. If pressure is applied to the joint, this aids wetting of the molten thermoplastics, and a weld forms as the joint cools [3, 4].

Ferromagnetic materials (such as stainless steel and iron) also heat up in a dynamic magnetic field due to hysteresis losses. As the magnetic field (B) increases, the ferromagnetic material becomes magnetized, and the magnetic intensity (H) increases. As the magnetic field decreases, so does the magnetic intensity. However, there is a lag between the two, which results in a hysteresis loop (Fig. 11.2). This phenomenon results in dissipation of energy in the form of heat.

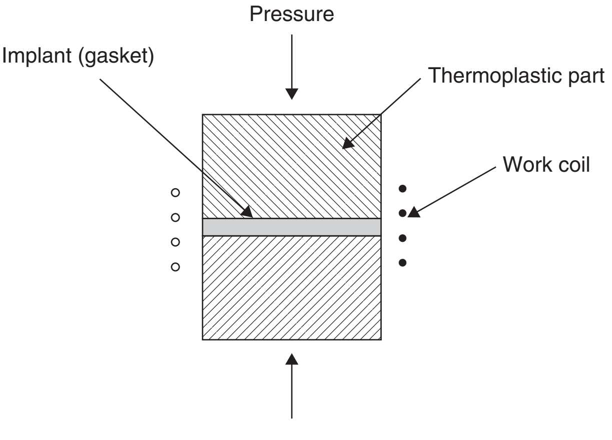


Figure 11.1. Set up for induction welding (Source: TWI Ltd).

The induction welding process can be divided into four main steps (Fig. 11.3):

Step 1: Placement of the Implant
Implants are available in many forms, such as sheets, extruded profiles, injection molded parts, tapes and strands (Fig. 11.4), depending on the size and shape of the parts to be welded, and on the position of the work coil. They can be positioned at the joint line, either by hand or by using an automated system [1, 5].

Step 2: Application of Pressure
Pressure can be applied to the parts by placing them in fixtures attached to a pneumatic cylinder, or the work

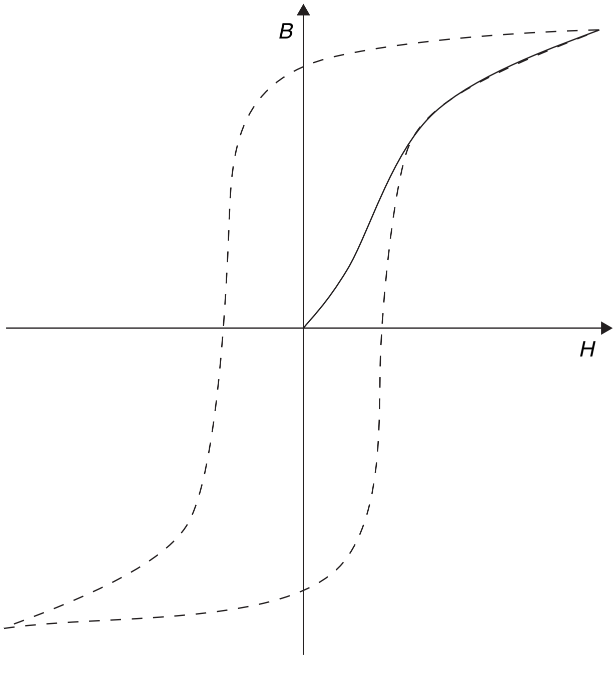


Figure 11.2. Graph of the magnetic field (*B*) in a ferromagnetic material and the magnetic intensity (*H*) for an alternating magnetic field. The magnetization curve is the full line and the hysteresis curve is the broken line. The area enclosed by the hysteresis loop is equal to the energy dissipated in one circuit (Source: TWI Ltd).

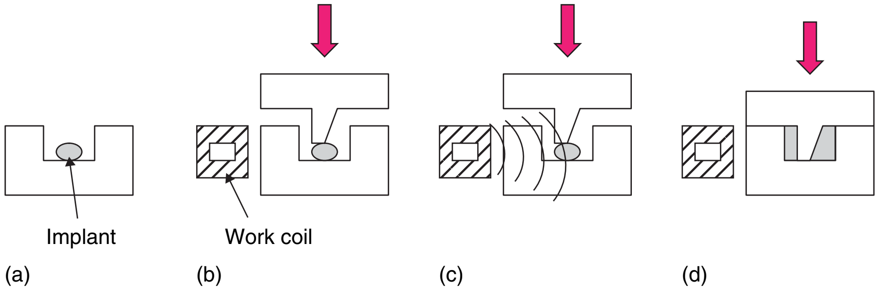


Figure 11.3. The induction welding process: (a) placement of the implant, (b) application of pressure, (c) induction heating, and (d) cooling under pressure (Source: TWI Ltd).

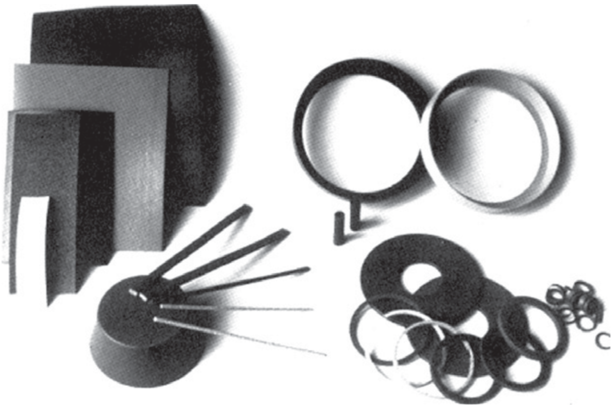


Figure 11.4. Various forms of induction welding implants (Source: Emabond Solutions).

coil may be embedded in a PTFE or ceramic block, which applies the pressure.

Step 3: Induction Heating
Power is applied to the work coil, creating the electromagnetic field that heats the implant, which in turn heats and melts the surrounding thermoplastic by thermal conduction. Electromagnetic fields become exponentially weaker as the distance from the work coil increases, so that joints placed as close as possible to the coil maximize the heating of the implant. During heating, the implant flows to fill the gap between the parts.

Step 4: Cooling and Removal of the Parts
After a preset time, the power is switched off and the parts are allowed to cool under pressure for a preset time. The welded assembly is then removed and the cycle is repeated.

Weld strength is proportional to the surface area of contact; however, it is important that the molten flow be contained within the joint area. The amount of molten material needed to fill the joint cavity can be calculated using the cross-sectional area of the implant (A_E), the cross-sectional area of the cavity between the parts being joined (A_V), and a constant (k) with values ranging from 1.02–1.05, depending on the pressure used in welding and the material being welded: $A_E = kA_V$. The constant (k) allows for overfilling the cavity and ensures that any surface irregularities are smoothed out during welding [1, 2, 6].

11.2 Advantages and Disadvantages

Induction welding provides structural, pressure-tight welds with most thermoplastics. It can be used to weld large parts, with bond lines up to 6.1 m (20 ft.) at one time. It can also be used to weld three-dimensional (3-D) joints with complex geometries, and multiple joints can be welded simultaneously.

High quality, stress-free welds in highly filled thermoplastics can be produced. The implant adds resin in the joint area to ensure good polymer to polymer linkage, even in cases of surface irregularities or wide tolerances between parts. Certain incompatible materials that cannot be welded with other methods can be joined by induction welding, regardless of melt temperatures. No prior surface treatment is necessary, and no distortion of the outside surface occurs. Heat is created precisely where needed, without causing thermal stresses in the main body of the part, and reject rates are low. Higher reliability of the weld is often obtained, with less sensitivity to changes in temperature and humidity, and welding is less dependent on properties of the materials being welded, such as color or melt temperature.

After welding, the joint can be reopened using the same equipment, in order to repair defective welds or open an assembly for internal repair or recycling.

Production cycles in induction welding are fast, with weld times typically ranging from 1 to 10 seconds, and the process is economical in its energy requirements, resulting in lower running costs.

The main disadvantages of induction welding are the additional cost of the implant, which can be significant, the cost of optimizing the configuration of the work coil, and the additional assembly operation of placing the implant at the joint. In addition, the presence of the implant can sometimes affect the mechanical performance of the joint [1, 2, 5–7].

11.3 Applications

Induction welding is frequently used for welding large or irregularly shaped parts that have been injection-molded, blow-molded, extruded, rotational-molded or thermoformed (Fig. 11.5), or for thermoplastics that are difficult to weld [6].

Probably the largest volume application is in the sealing of aseptic drink cartons, where an aluminum foil layer in the box wall is heated by induction to melt and seal the low density polyethylene (LDPE) coating.

In the automotive industry, the technique has been used to produce station wagon structural load floors and seatbacks composed of 40% glass-mat reinforced PP composite (Fig. 11.6) [2].

Figure 11.5. Examples of induction welded products (Source: Emabond Solutions).

Induction welding has also been used in the manufacture of a glass-filled PA 6 injection molded automotive intake resonator, with complex 3-D joints, where three separate welds were produced in the same welding cycle [2].

In the appliance industry, induction welding has been used in the manufacture of steam irons, dishwasher spray arms, and PP kettles (Fig. 11.7) [7].

In the electronics industry, sixteen 38.1 cm (15 inches) structural foam polycarbonate computer consoles were automatically assembled on a conveyor line. In the packaging industry, PP was welded to PE for a cosmetic container, using a continuous rotary sealer to provide a reliable leak proof seal at 150 parts per minute. Other applications include welding PP solar panels with a 4 ft. (1.2 m) bond line in 9 seconds, and PC blood oxygenators and arterial filter components for medical devices [6].

Other applications include sealing plastic-coated metal caps to plastic bottles, jointing of cross-linked PE (PEX) pipes, welding metal grilles to the front of loudspeaker units, and welding HDPE lawnmower shroud/gas tanks (Fig. 11.8) [1, 2, 8].

The feature of induction welds that allows them to be easily separated was taken advantage of in welding 50 mm (2.0 inches) threaded HDPE fittings directly to the opening of 95, 114, and 209 liter (25, 30, and 55 gallon) blow-molded drums (Fig. 11.9). For drum reconditioning, the fittings can be easily removed [2, 7].

11.4 Materials

Induction welding is less dependent than other welding methods on the properties of the materials being welded. It can be used to weld almost all thermoplastics, crystalline, and amorphous, and can weld high performance and difficult-to-weld resins. Dissimilar materials or thermoplastics containing glass, talc,

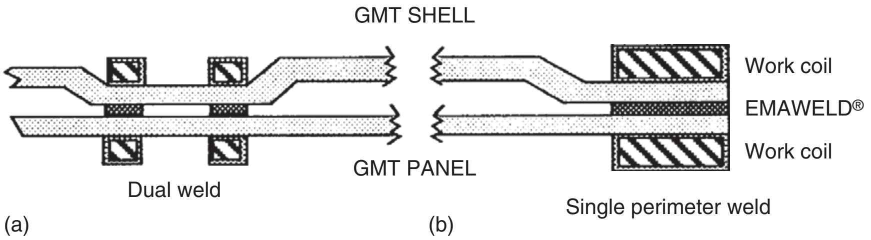


Figure 11.6. Induction welded joint designs for panels composed of a 40% glass mat reinforced PP composite used to produce station wagon structural load floors: (a) dual weld, placed at the interfaces of the flat panel and ribbed shell, (b) single weld, located at the end of the part (Source: Ref. [7]).

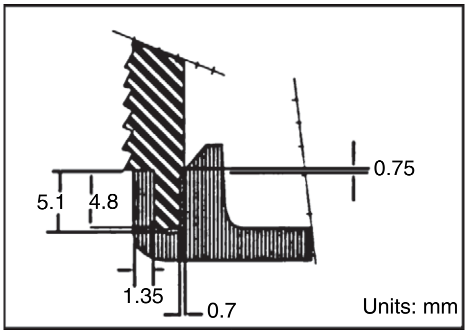
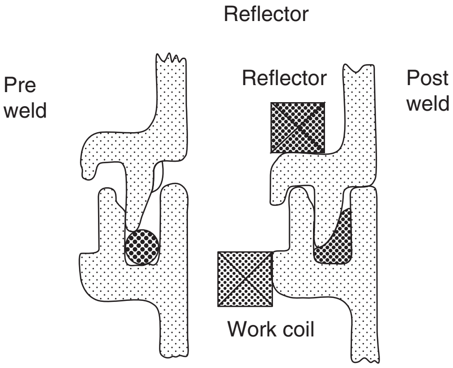


Figure 11.7. A polypropylene tea kettle joined using induction welding (Source: Ref. [7]).



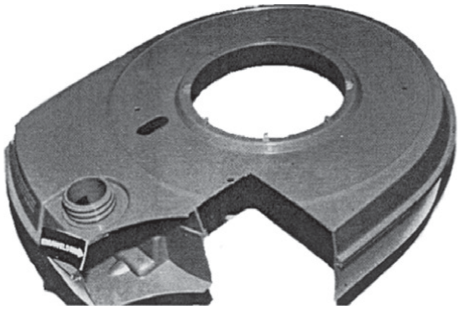


Figure 11.8. A polypropylene lawnmower shroud/gas tank welded using induction welding.

minerals, wood, or other fillers can be welded, and thermoplastic materials can be joined to nonthermoplastic materials, such as paper. When welding dissimilar thermoplastics, the thermoplastic matrix enclosing the ferromagnetic filler material consists of a blend of the two materials being welded. In welding filled materials, the amount of thermoplastic resin in the implant material can be increased to compensate for the filler content in the parts. A greater volume of melt will be produced during welding, resulting in a higher-strength bond. Reinforced plastics with filler levels up to 65% have been successfully welded [6, 7].

Work has also been carried out with thermoplastics such as PPS, PA12, and PP reinforced with glass and carbon fibers. Here substantially higher joint strengths were achieved with induction welding when compared with adhesive bonded and riveted joints [9].

11.4.1 Implant Materials

The electromagnetic material can be a metallic mesh or micron-sized ferromagnetic powders of different types (metallic, such as iron or stainless steel; or

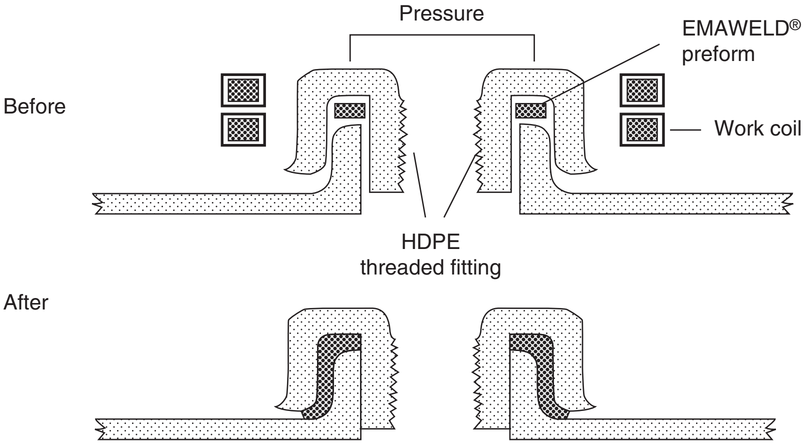


Figure 11.9. Polyethylene pipe fittings induction welded to a blow molded drum (Source: Ref. [7]).

nonmetallic, such as ferrite materials), particle sizes, and concentrations. For bonding thermoplastics, these electromagnetic materials are enclosed in a thermoplastic matrix that is compatible with the plastics being joined. In bonding thermosets such as sheet molding compound, an adhesive matrix surrounds the electromagnetic material. Heat is generated directly in the adhesive, providing a rapid cure; gel times as short as 30 seconds can be achieved in the cure of epoxies [1, 2, 6].

For bonding thermoplastic parts made from the same material, the matrix is generally the same material as in the part, and can be matched on melt flow. For dissimilar materials, a blend of the two thermoplastics is used. The implant formulation must be carefully considered for each application, and maximum efficiency may require production of a custom-made material [1, 5].

11.5 Equipment

A typical induction welding machine is shown in Fig. 11.10, and consists of five main parts: induction generator, work or induction coils, heat exchanger, press, and fixtures or nests.

Induction Generator
The induction generator converts at 50–60 Hz supply to a radio frequency (2–10 MHz), with a power typically between 1 and 5 kW, depending on the application. The impedance of the loaded work coil must be matched with the output impedance of the generator, in order to ensure a consistent and efficient operation of the system. This is referred to as tuning the coil.

Heat Exchanger
During the welding cycle, very high electric currents pass through the work coil. Therefore, to prevent it overheating, water is circulated through the coil and is cooled via a heat exchanger, which is often combined with the generator in a single unit.

Press
The system for applying the pressure during welding is normally a ram connected to a pneumatic (or sometimes hydraulic) cylinder.

Fixtures
Fixtures, or placement nests hold the parts together during the welding operation; one nest is generally fixed, and the other is movable. Nests are constructed using electrically nonconductive material, such as phenolic or epoxy, since the presence of a metal conductor

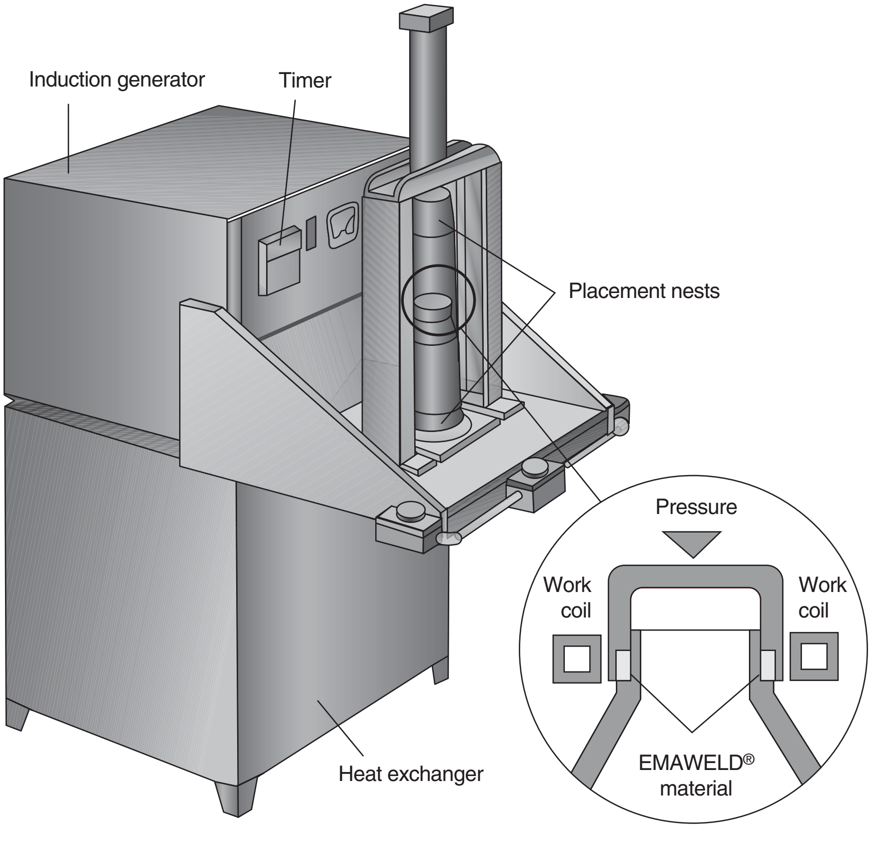


Figure 11.10. Typical induction welding machine. The inset shows the joint area with placement of work coils and implant (Emaweld material) (Source: Emabond Solutions).

near the work coil would reduce the intensity of the magnetic field.

Systems can be designed for in-line or rotary high-production sealing lines using programmable controllers and semiautomatic or automatic operation of the welding process. With automated equipment, a sealing rate of up to 150 parts per minute can be achieved.

Equipment costs range from tens to hundreds of thousands of dollars (US), depending on the size of equipment needed, automation desired, and the application [1, 5–7].

11.5.1 Work Coils

The function of the work coil is to provide the magnetic field around the joint. It should be compatible with the power output of the induction generator and designed to reduce tendencies for arcing or overloading at high frequencies [2].

Work coil design and positioning are important in achieving high-strength welds and process efficiency. Work coils should follow the contours of the joint and can be custom-made for each part. The distance between the coil and the joint (coupling distance) should be as small as possible, ideally less than 1.6 mm (0.063 inches); short coupling distances are essential because energy from the magnetic field used for heat generation is inversely proportional to the square of the distance from the coil. Coils can accommodate 3-D joints and can weld joints as long as 6.1 m (20 ft.). Copper reflectors can also be placed in the center of the coil to concentrate the magnetic field within the joint area [2, 10].

Coils are constructed from copper tubing, sheet stock, or machined blocks; all coils are water-cooled. Coils made from tubing can be round, square, or rectangular; common sizes are 3.2 mm (1/8 inch), 4.8 mm (3/16 inch), 6.4 mm (1/4 inch), and 9.5 mm (3/8 inch). Since constricted water flow in the 1/8 inch coil can contribute to overheating, this size is used only for short heating cycles and small parts, which are not affected by slight overheating. Square tubing is preferred over round tubing, in order to obtain optimum coupling distances. Copper sheet stock (1/16 inches, 1.6 mm thickness) is used for larger parts, up to 5 × 20 inches (127 × 508 mm) or 1 × 80 inches (25.4 mm × 2.03 m), and for sealing large surface areas and irregular flat shapes [2].

The simplest coil design is the single-turn coil (Fig. 11.11a), in which the magnetic field is concentrated around the inner diameter of the coil. A weak field intensity can develop at the end of the coil leads, which can be alleviated by use of a reflector. This coil requires less space than other designs. A multiturn coil (Fig. 11.11b) eliminates the weak field intensity of a single-turn coil. It can be cylindrical or helical for welding round containers, or rectangular, square or irregularly shaped, depending on the contours of the joint. Because the greatest magnetic field strength is within the perimeter of the coil, joints should be placed in the center of the coil. Reflectors are necessary for maximum efficiency when parts being joined are six inches (152 mm) or larger. The number of turns in the coil is dependent on the total surface area of the weld; the length of a multiturn coil should not be more than three to four times the coil diameter. Pancake coils (Fig. 11.11c) are used for heating large flat areas and they are made by winding tubing in a horizontal plane to a predetermined diameter [1, 2].

Hairpin coils (Fig. 11.11d) are single-turn coils squeezed together so that the coupling distance between the turns is equal to the part thickness. The magnetic field becomes more concentrated as the coupling distance is reduced. Hairpin coils can be formed into irregular shapes and are used for bonding long flat sheets or perimeter seals of structural components made from glass mat composites. For large parts, such as pipes or conduits, or for parts with limited access to the joint line, split coils (Fig. 11.11e) can be used. These coils can be opened for easy part removal [1, 2].

11.6 Joint Design

The five basic types of joint designs used in induction welding are shown in Fig. 11.12. The simplest design is the flat-to-flat joint, used for continuous welding operations, or for parts with a long weld line; this joint produces a structural weld and a static flow airtight seal. A flat-to-groove joint ensures accurate positioning of the weld and containment of the implant. It is used when the implant material needs to be automatically extruded into the joint interface. Highest strength welds are obtained with tongue-and-groove joints. The implant is completely contained within the joint, producing hermetic and pressure-tight seals and aesthetically pleasing welds. A shear joint is used for high-pressure container seals; the weld can withstand pressure from both inside and outside the container. A step joint, a modification of a shear joint, can accommodate wide variations in part shrinkage and produces a high-pressure, hermetic seal [1, 2].

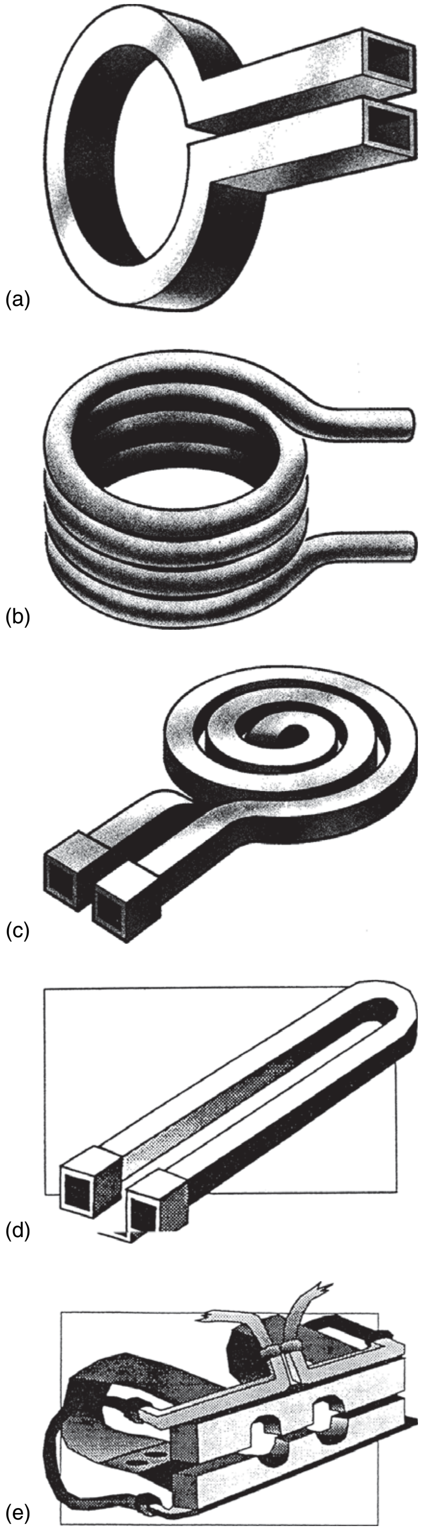


Figure 11.11. Common designs of work coil used in induction welding: (a) single-turn, (b) multiturn, (c) pancake, (d) hairpin, and (e) split (Source: Emabond Solutions).

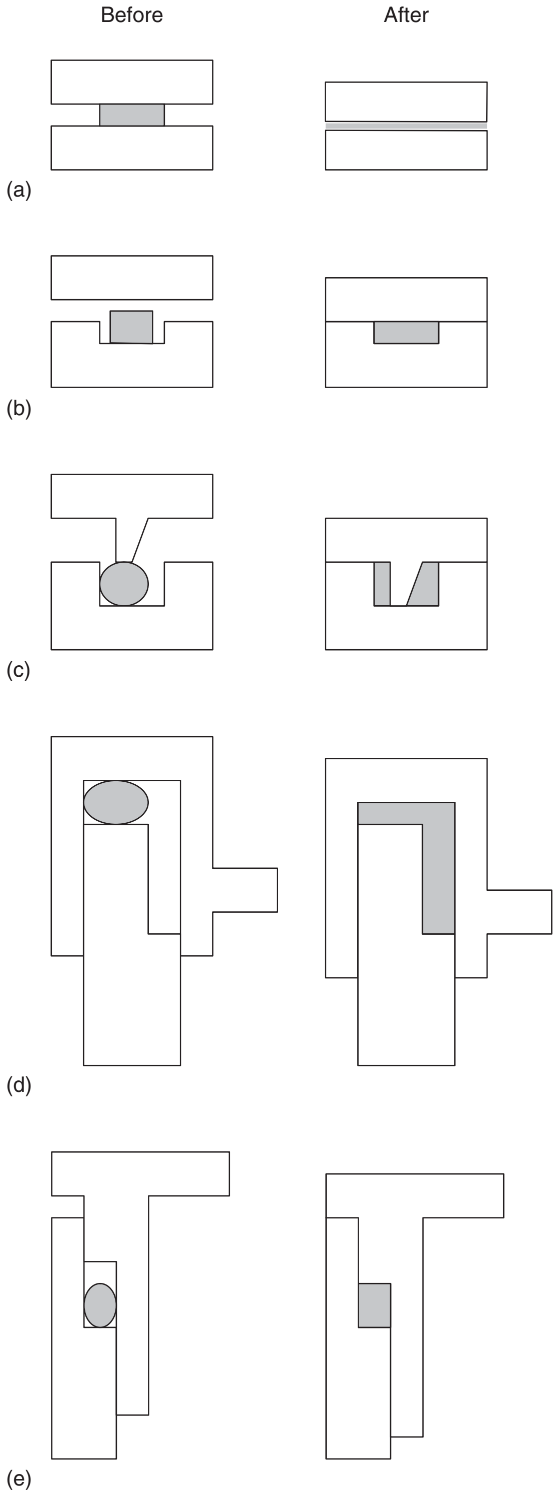


Figure 11.12. Joint designs commonly used in induction welding: (a) flat to flat, (b) flat to groove, (c) tongue and groove, (d) shear, and (e) step (Source: TWI Ltd).

11.7 Welding Parameters

The main welding parameters in induction welding are: power, weld time, weld pressure, and cooling time.

Typical induction powers are in the range of 1–5 kW. Higher power output is necessary for larger parts or parts with greater joint length. The power output must also increase as the coupling distance between the joint and the coil increases.

Weld time is dependent on the type and particle size of the electromagnetic filler, the cross-sectional area of the electromagnetic filler enclosed in the thermoplastic matrix, power output, frequency, and part size. These parameters are tailored for each specific application [2, 5].

The weld pressure ensures an even distribution of the implant inside the joint. Cooling times vary depending on the application, but can be less than one second.

Other important factors in induction welding include the design of the joint and work coil, magnetic field frequency, and the type of electromagnetic material.

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12 Heat Sealing

12.1 Process Description

Heat sealing is used for joining thermoplastic films, typically less than 0.5 mm (0.02 inches) thick. There are two main types of heat sealing: hot-bar welding and impulse welding.

12.1.1 Hot-bar Welding

Hot-bar welding is based on the principle that if two thermoplastic films are pressed against a heated metal bar, they will soften and a joint can be made between them. Since the technique relies on the conduction of heat through one of the films, this limits the thickness of material that can be welded. Sometimes two heated bars are employed, one either side of the films, which has the effect of reducing the welding time.

The equipment comprises of one or two metal bars, which are generally electrically heated. Normally, one of the bars is hinged to allow the placement and removal of the thermoplastic films. The weld pressure is applied mechanically by the operator or via pneumatic cylinders. A coating of PTFE is often applied to the bars to prevent softened or molten thermoplastic from adhering to them (Fig. 12.1).

The welding parameters important to this process are bar temperature, weld pressure, and weld time. Hot-bar welding can be a rapid process with typical weld times in the order of 1–3 seconds for 100 μm (0.004 inches) thick films.

With conventional hot-bar welding, the heated bar is removed while the weld is still molten, therefore the joint is not under pressure during the cooling phase. This can sometimes lead to reopening of the weld after the bars are released, especially if the films are under tension. In an attempt to solve this problem, a new variant of hot-bar welding, called heated tool/cooled tool welding, has been developed where cooling pressure is applied with the aid of a cooled tool, which replaces the heated tool after the heating cycle has elapsed [1].

Another variant of hot-bar welding is continuous heat sealing, where the heated bars are replaced with heated belts or rollers.

12.1.2 Impulse Welding

Impulse welding is one of the most commonly used joining methods for sealing packaging materials. Typically, this welding technique is used for making straight heat seal lines, although complex joint requirements for some packaging applications have seen the recent development of curved or three-dimensional seal lines.

In impulse welding, the film layers to be sealed are usually placed between two jaws, at least one of which contains a nickel-chromium resistance wire strip. The strip is typically encapsulated with a nonstick coating such as PTFE to ensure that the molten film does not

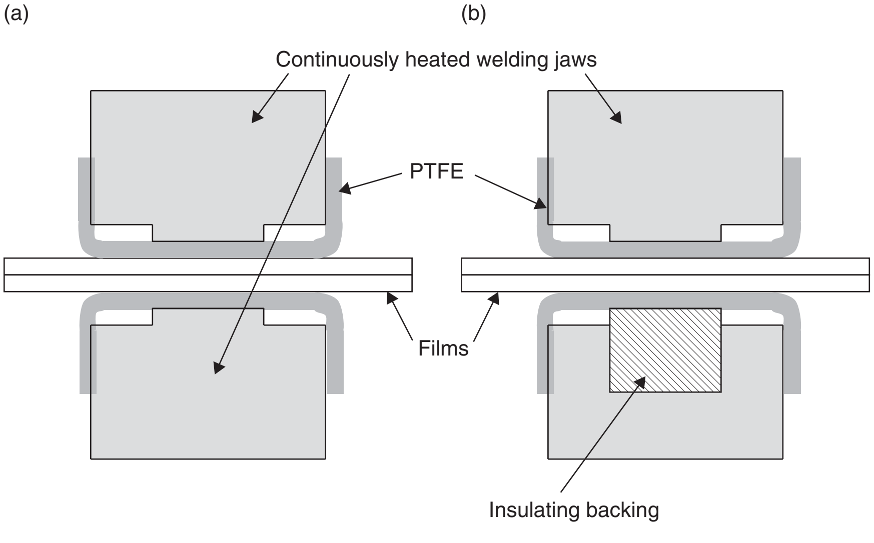

Figure 12.1. Schematic of hot-bar welding: (a) two-sided heating, (b) single-sided heating (Source: TWI Ltd).

stick to it (Fig. 12.2). The width of the wire strip determines the width of the weld. Once the jaws have clamped onto the film layers, a pulse of electrical current is passed through the wire, causing the temperature of the wire to rise rapidly and transfer heat to the film layers. Critically, the films melt at the interface and co-solidify during the cooling cycle to form a weld. Pressure is applied to the films to ensure that the molten surfaces are in intimate contact during the heating and cooling phase.

In conventional impulse welding, the temperature and pressure are not controlled during the welding cycle. This can be problematic because the temperature of the wire will tend to creep up after each successive heating cycle. To overcome this problem, controlled impulse welding is now available, where the heated element engages the films at an accurately preset temperature and pressure. Typically, the pressure is controlled pneumatically to ensure that a constant welding force is applied to the films. The welding temperature is controlled with high-response controllers that allow the material to heat, without the risk of overheating. This is followed by a controlled cooling cycle under pressure, until the material has solidified. This welding cycle can be completed in milliseconds [2].

12.2 Advantages and Disadvantages

The main advantages and disadvantages of heat sealing are given in Table 12.1.

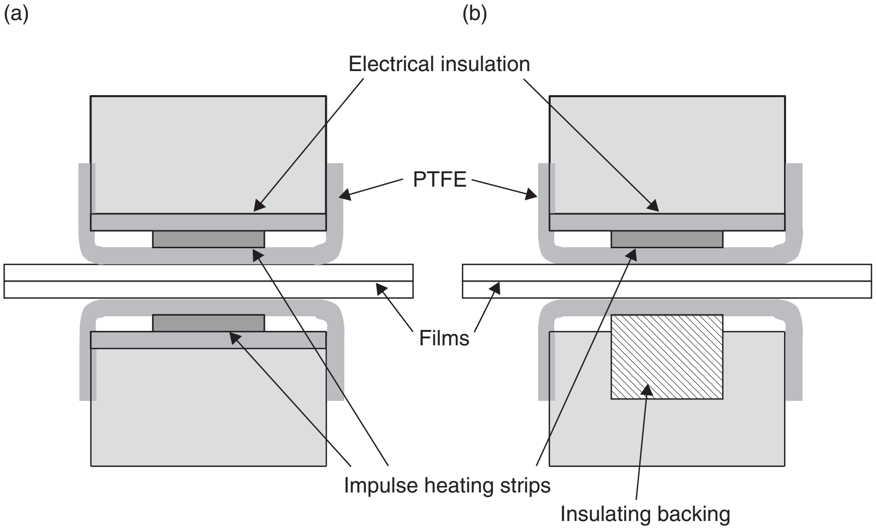

Figure 12.2. Schematic of impulse welding: (a) two-sided heating, (b) single-sided heating (Source: TWI Ltd).

Table 12.1. Advantages/Disadvantages of Heat Sealing

Advantages	Disadvantages
Limited voids or porosity No consumable needed Small or no weld bead No grinding of weld flash necessary for mass production Simple joint design Fast welding cycle times Exceptional seal integrity at low temperatures No adhesives or consumable that could contaminate the product Peelable and pierceable seals More cost-effective than other sealing methods Optically clear seals possible Energy efficient (impulse welding)	Heat is applied to the outside of the film, resulting in energy losses and reduced efficiency Can only be used for thin films, up to 0.5 mm (0.02 inches) Heat transfers to product inside packaging when hot-bar welding Limited to relatively simple joint designs Failures can occur due to creases in the seal area Misalignment of parts or machine jaws can lead to leakages

12.3 Applications

Hot-bar welding and impulse welding have found applications in a number of industrial sectors, but is most widely used in the packaging industry for sealing bags, films, and containers made from thermoplastics. This includes plastic pot and tray sealing for food packaging applications (see Fig. 12.3).

A preformed container, tray, or pot can be sealed with a plastic film, foil or paper lid. This lid can either be precut or fed from a reel of the material. The lidding material is laid over the open face of the container and is heat sealed to the container. Sealant layers on the tray and lid cause a bond to form during the heat sealing process. However, it is always worth considering the risk of contamination (e.g., food or oil) on the tray or film—this will have an impact on the seal strength achieved. If contamination is present, it may be necessary to change the sealing parameters set on the machine.

Many medical devices are also heat-sealed in packages of thermoplastic and plastic coated paper. The heated region can be textured to reduce and control the joint strength. This offers the opportunity to supply a sterile component in an easy-to-open package. Outer packets for intravenous bags, laminated packs for powders, colostomy bags, and some tablet blister packs are also heat-sealed (Fig. 12.4).

Heat sealing can also be used for sealing membranes in filter units (Fig. 12.5).

In addition to medical and packaging applications, some electronic devices are also joined together by heat sealing, including printed circuit boards, electronic packages, and liquid crystal displays (Fig. 12.6).

Figure 12.3. Examples of heat-sealed food packages (Source: Packaging Automation Ltd).

Figure 12.4. Heat-sealed blister pack (Source: TWI Ltd).

Figure 12.5. Heat-sealed medical membrane filter (Source: Thermal Press International).

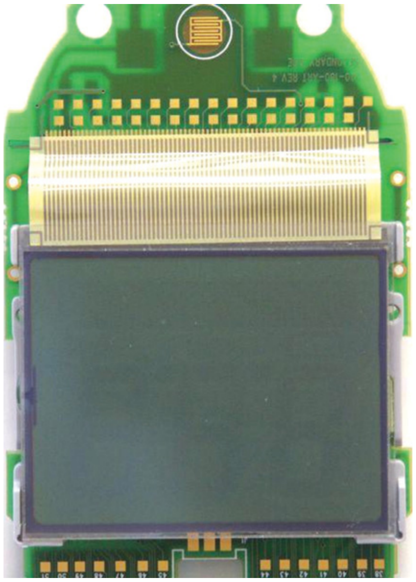

Figure 12.6. Heat-sealed liquid crystal display (Source: Thermal Press International).

12.4 Materials

Unlike some welding and sealing techniques, such as radio frequency (RF) welding, heat sealing is not material dependent, and can be used for joining many different types of thermoplastic materials. Below is a list of considerations to be kept in mind when selecting a material for a packaging application.

- The product contained in the package may mean one material is more suitable than another.
- The choice may be dictated by the cost of the material.
- Marketing and consumer perception may influence the choice because of the aesthetic qualities of the material.
- Both parts of the packaging must be compatible.

The use of polyethylene, either as LDPE, linear low density polyethylene (LLDPE) or as a mixture or blend involving combinations of LDPE, MDPE, HDPE, EVA, etc, finds a wide usage in heat sealed bags, sachets, and shrink wraps. PP, PVC, PS, IPS, PA, aluminum foil, and board materials are all heat sealable and are also extensively used in the packaging industry. Films used for heat sealing applications are manufactured in two different ways:

- Mono layers—a single layer of material often with an adhesive (lower melting point) coating. Different coatings used include amorphous PET (used for high temperatures, e.g., cooking), EVA (used for microwave products) and PE.
- Laminates—multilayer films formed from two or more different substrate materials. The sealant layer is dictated by the material, the type of seal needed (e.g., weld or peel) and cost.

Selecting packaging materials for medical applications requires careful consideration of the functional requirements of the package and the method of packaging. The critical nature of sterility maintenance requires a thorough understanding of the design and function of the medical device and the machinery being used to package it. For packaging systems employing a heat seal, the user is faced with several material options. Heat sealable materials used in the medical industry include polyethylene, polyamide, polyester, polypropylene, polycarbonate, and polystyrene.

12.5 Equipment

12.5.1 Hot-bar Welding

Hot-bar welding equipment is simple to set-up and usually comprises of a heated tool coated with a nonstick material, such as PTFE. The heated tool is normally heated electrically and the temperature is constantly regulated. The heated tool is mounted on a press or ram that can be controlled pneumatically or hydraulically. The films to be welded are usually mounted on a heat-insulating material. An example of a hot-bar welding set-up is shown in Fig. 12.7.

12.5.2 Impulse Welding

Standard impulse sealers weld up to 250 μm (0.01 inches) film without difficulty; double-element machines are available for repetitive sealing of heavier gauge and gusseted materials. Impulse heat sealers use low voltage, nickel-chromium resistance wires that heat up rapidly to the desired temperature. The element then cools, allowing the molten polymer to solidify under pressure.

Typically, impulse sealers are fitted with electronic timers to accurately control the welding period. Most heat sealers also include a timer that indicates the

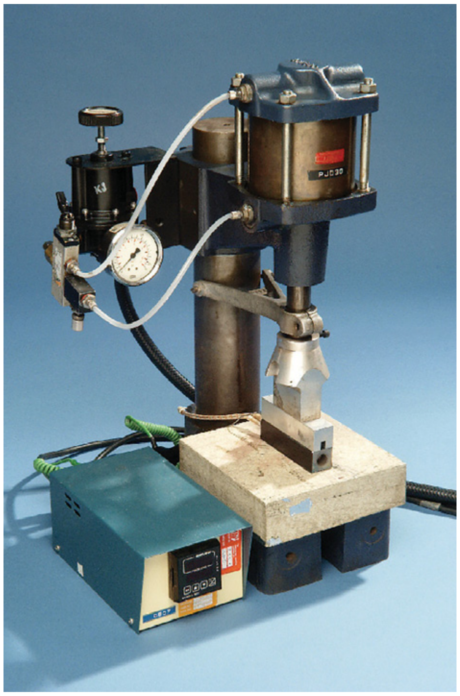

Figure 12.7. Hot-bar welding machine (Source: TWI Ltd).

cooling period, helping to control the quality and consistency of seals. Other parameters are often preprogrammed into the machine, making it easy to use and consistent in operation. Safety cutters are available on many models to trim surplus material or to make bags from lay-flat tubing. Wide seal elements for specialist applications and cut-and-seal elements are also available.

Most heat sealing machines are supplied with rollers and trays that allow the material to be easily manipulated through the heat sealer (Fig. 12.8).

12.5.3 Automatic Heat Sealing

Developments in heat sealing for the food packaging industry has led to machine designs that are compact, space saving, fully automatic, and seal packages at extremely high speeds. Automatic machines combine the simplicity of use and flexibility associated with manual heat sealing machines, but encompass advanced control systems and production speeds of up to 72 pack seals per minute (Fig. 12.9).

Automatic heat sealing machines can also have the following features:

- Atmospheric, gas flushing and vacuum flushing
- Capable of sealing plain or printed film to any compatible container
- Very quick and simple tooling changes
- Touch sensitive control screens, allowing preprogramming of sealing parameters and tools for quick and simple product changes
- Data logging of production information
- Diagnostic capabilities, which include the identification of specific devices that have failed within a safety circuit.

12.5.4 Continuous Heat Sealing

Continuous heat sealers provide the capacity for continuous, high-quality package sealing. Most sealers

Figure 12.8. Impulse welding polyethylene bags (Source: TWI Ltd).

Figure 12.9. Fully automatic heat sealing equipment for food packaging (Source: Packaging Automation Ltd).

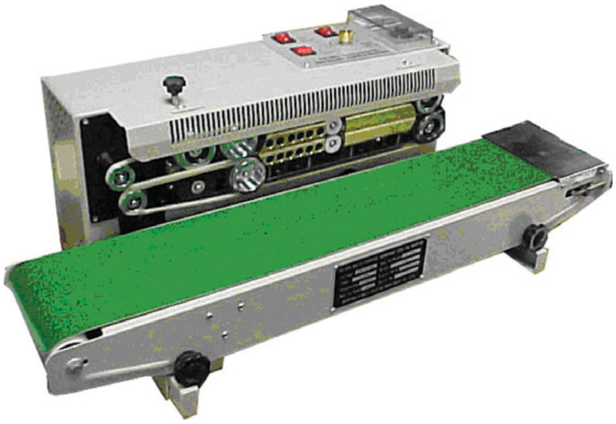

Figure 12.10. Belt-fed continuous heat sealing machine (Source: Simplesealers).

use moving heated belts to seal packaging material (Fig. 12.10). Other machines use heated rollers that simultaneously apply heating, pressure, and cooling. Typically, unsealed bags, pouches, or sheet material are fed into the belts by an operator. Some heat sealers also incorporate an auto-leveling system and a conveyor, so that the operator does not need to feed the material through the sealing operation.

Continuous heat sealers are useful for small- to medium-sized package sealing. Sealing speed and temperature is adjustable, allowing for high throughput sealing of a variety of different materials and thicknesses. They are more complicated than hot bar or impulse sealers, as they contain more moving parts. The use of belts and a conveyor requires a motor, gearing, and a more sophisticated electronic control system. This adds to the cost, and may also mean additional maintenance.

12.6 Welding Parameters

The two main welding parameters for heat sealing are time and temperature. However, to ensure that consistently good quality seals are produced, other process parameters should also be controlled, including:

- Sealing environment
- Jaw/platen geometry
- Preheat
- Element design
- Heating temperature control
- Cooling temperature control
- Sealing pressure

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13 Flash-Free Welding

13.1 Process Description

Flash-free welding, as its name implies, describes welding techniques that do not produce any weld flash. It can be applied to pipes, solid extrusions (such as rods), and sheets.

13.1.1 Welding of Pipes

The principle of flash-free welding is to totally constrain the melt during the welding process. This is done by either having a heated metal collar, as in bead-and-crevice-free (BCF) and weld-in-place (WIP) welding; or a consumable electrofusion-type fitting, as in high-performance fusion (HPF) welding, on the outside of the pipe and an inflatable elastomeric bladder, positioned at the joint line, on the inside (Fig. 13.1).

In the BCF system, the pipes to be welded are cut to the required length and the ends are faced to ensure that they are flat and square. The surfaces of the pipes, the heated collar, and the bladder are then cleaned using ethyl alcohol wipes. The first pipe is inserted into the welding machine so that the end is positioned exactly in the middle of the heated collar, and the clamps are locked to prevent axial movement during welding. The bladder is then inserted into the pipe and so positioned that half of its length is protruding from the pipe end. The second pipe is then inserted and positioned so that there is no gap between the pipe ends, and is then clamped in place (Fig. 13.2). The bladder is inflated to around 60 psi (0.4 MPa) and the heater is switched on for a preset time, at the end of which the joint is allowed to cool to a preset temperature with the bladder still inflated. An example of the resulting joint is shown in Fig. 13.3 [1].

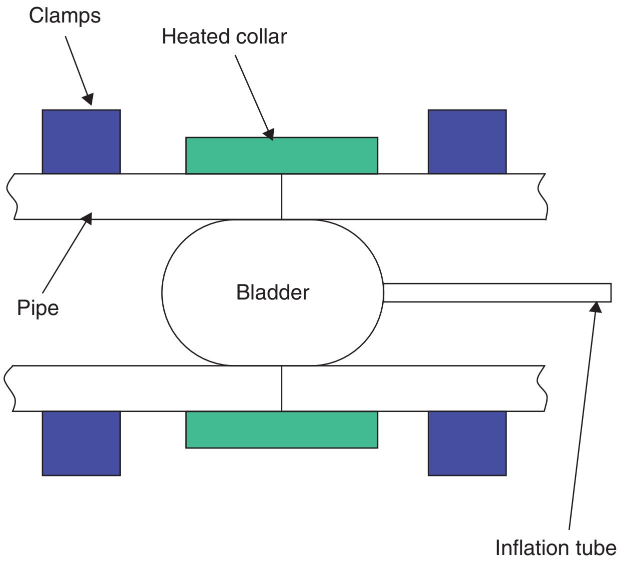

Figure 13.1. Principle of flash-free welding of pipes (Source: TWI Ltd).

For solid extrusions, the principle is the same, but the constraint is only on the outside.

13.1.2 Welding of Sheet

Flash-free welding of sheets is often known as flow-fusion welding. In this arrangement, the heating elements and constraints are on the top and bottom of the joint (Fig. 13.4). An example of a flow-fusion weld is given in Fig. 13.5.

13.2 Advantages and Disadvantages

The primary advantage of flash-free welding is that the joints have no beads or flash. This is very important in applications where high purity and cleanliness are of priority; the existence of beads on the inside of pipelines creates "dead flow" areas where contamination or bacterial growth can accumulate. Also, the notch created by a weld bead is an area of higher stress concentration, which can reduce the long-term integrity of the joint, especially if it is also in contact with aggressive fluids.

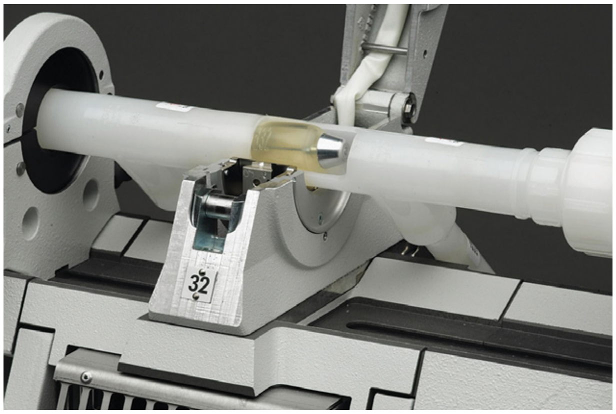

Figure 13.2. Positioning of the pipes and bladder during BCF welding (Note: The joint area is cut away to show the position of the bladder). (Source: Georg Fischer Piping Systems).

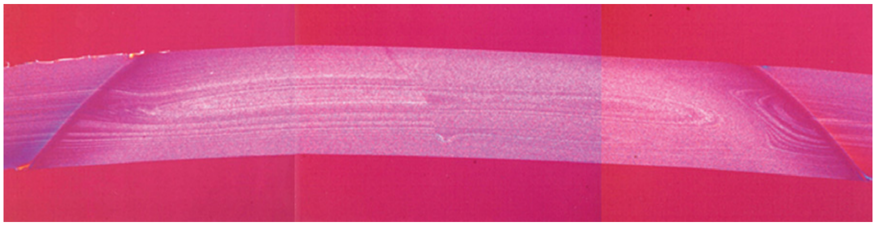

Figure 13.3. Cross-section of BCF joint (Source: Georg Fischer Piping Systems).

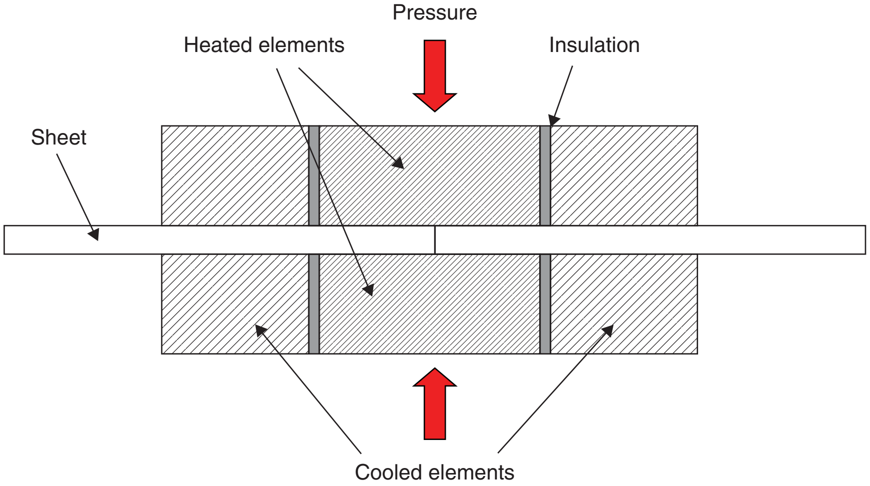

Figure 13.4. Principle of flash-free welding of sheets (Source: TWI Ltd).

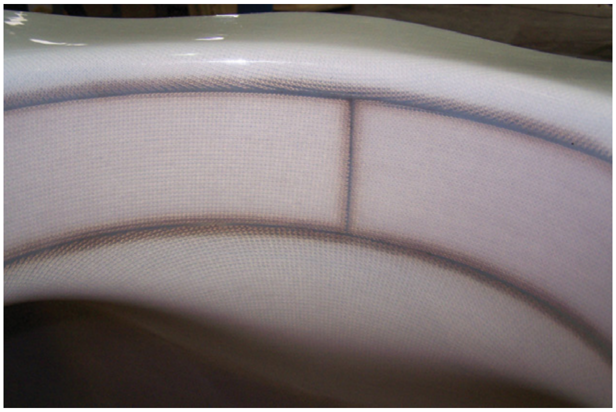

Figure 13.5. Flow-fusion welds in 2.3 mm (0.09 inches) glass-fabric-backed fluorinated ethylene propylene copolymer (FEP) sheet (Source: Plastichem Ltd).

The main disadvantage of flash-free welding is the fact that it relies on the conduction of heat from the surface of the part through the full thickness. This results in long welding cycles and restricts the maximum wall thickness that can be welded by this method to around 3 mm (0.12 inches).

13.3 Applications

The main applications for flash-free welding of pipes are in the semiconductor, pharmaceutical, and food processing industries, which require the transportation of fluids with no possibility of contamination. For this reason, the welding operation is often carried out under clean room conditions [2].

In the plastics fabrication industry, flash-free welding of sheets is carried out for applications where the storage of high purity and/or highly aggressive chemicals is required.

13.4 Materials

Flash-free welding is mainly used for welding fluoropolymer, such as PVDF or perfluoroalkoxy resin (PFA), or PP pipes, of outside diameters between 20 mm (0.8 inches) and 63 mm (2.5 inches), and fluoropolymer (PVDF, ethylene chlorotrifluoroethylene copolymer (ECTFE), FEP, or PFA) sheet, of thicknesses between 0.5 mm (0.02 inches) and 3 mm (0.12 inches).

13.5 Equipment

Three commercial welding systems are available for the flash-free welding of pipes:

- Bead-and-crevice-free
- High performance fusion
- Weld-in-place

The BCF system (Fig. 13.6) was developed for welding PVDF and PP pipes up to 63 mm (2.5 inches) outside diameter (OD) and comes with a set of interchangeable heating collars for different pipe sizes. The welding parameters are programmed into the machine and the welding cycle is carried out automatically. The heating/clamping carriage can be disconnected from the control unit to allow in situ welding (Fig. 13.7) [1].

The WIP system was developed specifically for PFA pipes up to 2-inch (50 mm) OD. It is similar to BCF but uses a hand-held heating collar and does not have a separate clamping system. Again, the welding cycle is fully automatic and is performed via a remote control unit.

Figure 13.6. BCF welding machine (Source: Georg Fischer Piping Systems).

Figure 13.7. In situ BCF welding (Source: Georg Fischer Piping Systems).

The HPF system is used for PVDF pipes up to 63 mm (2.5 inches) OD. It is similar to the electrofusion welding technique (Chapter 10) in that it uses an injection-molded fitting containing a coil of heating wire. However, rather than having two heating zones within the fitting, it has only one, in the middle of the fitting (Fig. 13.8) [3].

Flow-fusion welding equipment for sheets tends to be made in-house as bespoke systems.

13.6 Welding Parameters

The main welding parameters for flash-free welding are weld temperature, heating time, and cooling time, all of which depend on the wall thickness/pipe diameter and material type. The welding times for the HPF system are given in Table 13.1 [3].

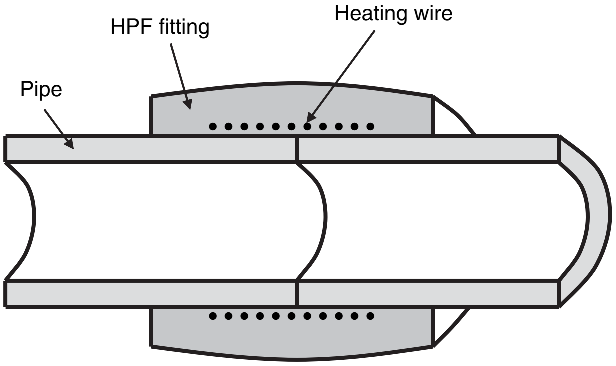

Figure 13.8. Schematic of HPF welding system (bladder not shown) (Source: TWI Ltd).

Table 13.1. HPF Welding Times

Pipe Outside Diameter (mm)	Welding Time (s)[a]
20	480
25	500
32	785
40	645
50	820
63	810

[a] Includes 300 s cooling time.

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14 Friction Stir Welding

14.1 Process Description

14.1.1 Rotational Friction Stir Welding

Friction stir welding (FSW), developed by and proprietary to TWI Ltd in the UK, is an advanced technique for joining materials in a continuous operation. In conventional FSW, a cylindrical, shouldered tool with a profiled probe is rotated and slowly plunged into the joint line between two pieces of sheet or plate material, which are butted together (Fig. 14.1). The parts are clamped to prevent the abutting joint faces from being forced apart during the welding process. Frictional heat is generated between the wear resistant welding tool and the materials to be joined. This heat causes the latter to soften or melt, and allows traversing of the tool along the joint line. The plasticized material is transferred from the leading edge to the trailing edge of the tool probe and is forged by the intimate contact of the tool shoulder to produce a weld between the two pieces. The process can be regarded as a keyhole welding technique since a hole to accommodate the probe is generated, then filled during the welding sequence [1].

Although very successful at welding metals, especially aluminum alloys, conventional rotational FSW presents the following problems when welding plastics:

- Difficulty in retaining the material at the joint line, resulting in voids in the welded joint
- Low speed of welding
- Difficulty in creating an even polymer mixing at the joint line
- A nonuniform crown or weld bead

To solve these problems, Brigham Young University developed a hot shoe tool (Fig. 14.2) through which the rotating probe passes. With this arrangement, heat is not produced by frictional heating from the shoulder, but by the hot shoe that also constrains ejection of molten material from the joint line [2, 3].

14.1.2 Vertical Reciprocating FSW

The principle of vertical reciprocating FSW is shown in Fig. 14.3. It consists of a blade that reciprocates in the vertical direction. Frictional heat is generated between the blade and the plastic material. The

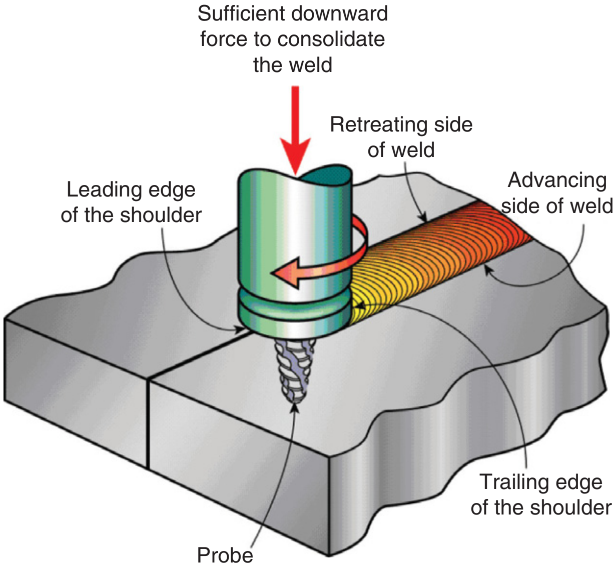

Figure 14.1. Principle of rotational friction stir welding (Source: TWI Ltd).

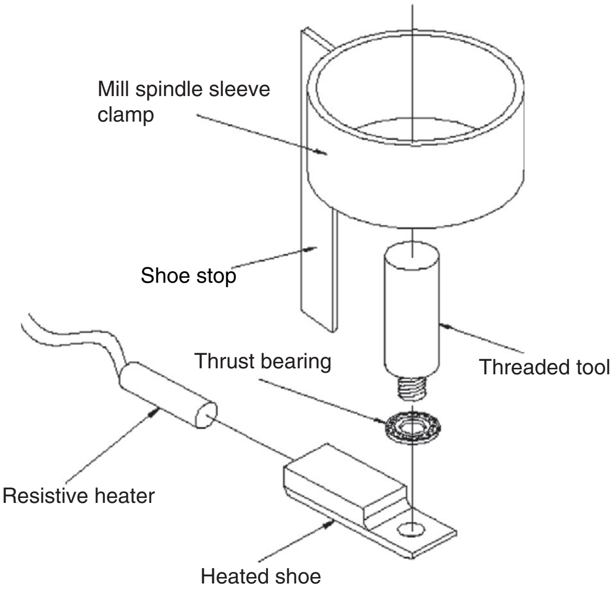

Figure 14.2. Heated shoe system for rotational FSW of thermoplastics (Source: Ref. [2]).

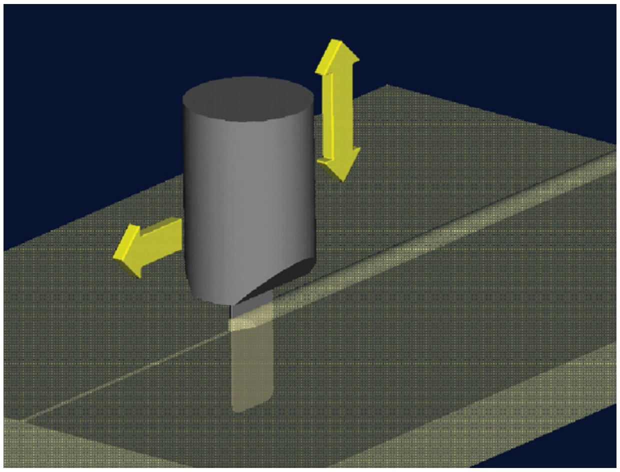

Figure 14.3. Vertical reciprocating FSW (Source: TWI Ltd).

main problem with this technique is that there is no mechanism for retaining molten material in the joint, which results in voids in the weld area and associated low weld strength.

14.1.3 Viblade Welding

Another variant of FSW is the reciprocating motion of a blade in the direction of the weld, as shown in Fig. 14.4. This technique has the benefit that the blade remains fully within the joint at all times, making it easier to contain the melt in the weld. In addition, heat losses are reduced, and the mean temperature should be higher when compared with vertical reciprocating motion [4].

A photograph of a Viblade weld is shown in Fig. 14.5.

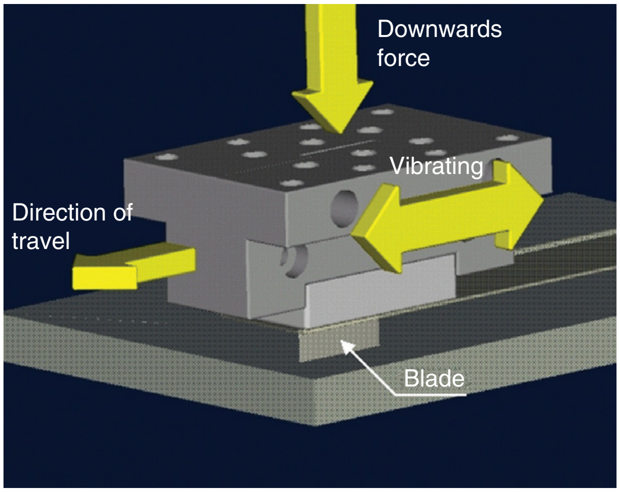

Figure 14.4. Schematic illustration of Viblade welding (Source: TWI Ltd).

Figure 14.5. Viblade weld in 9 mm (0.35 inches) thick PP sheet (Source: TWI Ltd).

14.2 Advantages and Disadvantages

The potential advantages of Viblade welding over existing fabrication welding techniques, such as hot gas and extrusion welding, include: increased productivity, especially for thicker sections (>10 mm; >0.39 inches); continuous welding possible; ability to weld almost all thermoplastics; simple joint design; practically flash-free welds; and the fact that it is an automated process, resulting in improved QA and a reduction in weld failure.

The limitations of the FSW process at present are that it has only been proven for producing linear welds, and it is not currently commercially available for joining plastics.

14.3 Applications

The increased use of plastics in manufacturing and fabrication has highlighted the need for new joining techniques to be developed to improve productivity and achieve more consistent welds with greater integrity. The current techniques used for welding thick section thermoplastic sheets for the manufacture of large constructions, such as chemical storage vessels and tanks, are extrusion, hot gas, and butt-fusion welding. Both hot gas and extrusion welding rely on the skill and consistency of the operator to ensure that a quality weld is made. Automated FSW could potentially replace these manual techniques for fabricating large thermoplastic structures and vessels, whilst ensuring that a weld of high quality is maintained. The FSW of thermoplastics has not yet been commercially exploited; however the FSW process could have a significant impact for continuous welding of plastic sheet.

14.4 Materials

FSW can be used for joining many types of materials, if tool materials and designs can be found that allow the material to melt and flow. Joint strengths of over 95% of parent strength have been obtained in the laboratory for ABS, PP, and HDPE. Other materials successfully welded include PVC and PVDF [2].

14.5 Equipment

14.5.1 Rotational FSW

Rotational FSW can be carried out on simple machinery, such as a modified vertical milling machine. The machine frame needs to be robust, avoiding any significant deflection during welding. Ample power is needed to ensure a steady rotation of the welding tool. The parts to be welded should be manipulated by a linear or X–Y table. A hydraulic force system can also be incorporated into the machine to provide the downward welding load.

14.5.2 Vertical Reciprocating FSW

The principle of vertical reciprocating FSW is that a specially profiled metallic tool (or probe) is moved relative to the joint to generate heat by friction. The tool can be either cylindrical in shape or an aerofoil-shaped, blade-type probe. The tool is reciprocated with predetermined amplitude before being traversed along the length of abutting sheet materials.

A machine can be used that allows for the creation of reciprocating stroke movement. This type of movement is created by means of a Scotch-yoke mechanism.

The Scotch-yoke is a mechanism for converting the linear motion of a slider into rotational motion or vice versa. The piston or other reciprocating part is directly coupled to a sliding yoke with a slot that engages a pin on the rotating part.

This type of system, combined with a mechanism for applying horizontal load and manipulating the polymer parts or blade can be used for vertical reciprocating FSW.

14.5.3 Viblade Welding

Currently, a commercial linear vibration machine is used for Viblade welding. The welding process consists of a blade (made of titanium) and a shoulder (made of PTFE) that run between the abutted thermoplastic sheets, whilst a downward force is applied. The blade and shoulder vibrate at a frequency of around 200 Hz and with an amplitude of approximately 1.15–1.3 mm (0.045–0.05 inches). The reciprocating blade generates frictional heat, causing the sheet material at the interface to melt and form a weld behind the blade.

14.6 Welding Parameters

There are a number of process and material variables for all the FSW techniques detailed in this section which can affect the quality of FSW of thermoplastics. These include:

- Tool design
- Tool rotation speed
- Tool temperature
- Travel speed
- Vertical load
- Horizontal load
- Plunge depth
- Tilt angle
- Welding gap
- Plate thickness variation

For Viblade welding, since thermoplastics have a very low thermal conductivity, the heat produced by the shoulder is not enough to melt the material near the root of the joint. A blade that produces enough heat input on the faces of the butt-joint is required. The frictional heat is proportional to the pressure, so the downward force directly acts on the heat input produced by the shoulder, and indirectly on the heat produced by the blade. The pressure between the blade and the faces of the sheets is due to a horizontal load applied to the sheets, and also the penetration of the blade between them. The horizontal load can be applied to the abutting sheets either pneumatically or mechanically. The vertical load of the shoulder also helps to prevent the gap between the sheets (caused by the advancing blade) to expand. This results in a high pressure on the blade faces and a frictional heat input enough to melt the material through the full thickness.

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15 Microwave Welding

15.1 Process Description

Microwave welding is a form of electromagnetic welding, similar to radio frequency, laser, induction and IR welding, but using a radiation frequency of typically 2.45 GHz. Since most thermoplastics do not experience an immediate temperature rise when irradiated with this frequency of radiation, this technique normally works by placing a microwave energy absorbing material, in the form of a gasket, at the joint interface. The heat generated in this implant then melts the surrounding thermoplastic, producing a weld upon cooling. However, some thermoplastics, that is, those containing polar groups as part of their molecular structure, such as ABS, PVC, nylon, and PVDF, will heat in a microwave field and can be welded directly.

Absorption of microwave energy in polar, conductive materials is dependent on the conductivity (σ) of the material, the dielectric constant (ε), the dielectric constant in a vacuum (ε_0), the frequency of the radiation (ω), the imaginary part of the dielectric constant (ε'') which accounts for dielectric loss through energy dissipation, and the real part of the dielectric constant (ε') which represents the ability of the material to store electrical energy. A measure of the ability of the material to absorb microwave energy is given by the loss tangent, $\tan \delta$, where [1]

$$\tan \delta = (\sigma/\varepsilon_0 \varepsilon \omega) = (\varepsilon''/\varepsilon').$$

The heating of a material in a microwave field is proportional to $\tan \delta$. However, since the loss tangent is a function of temperature and also the time at temperature, it is difficult to predict the amount of heating accurately.

The microwave implant welding process consists of five steps:

(1) *Application of Implant*: A consumable, microwave susceptible implant is applied at the joint interface.

(2) *Clamping*: The parts to be joined are clamped together to ensure that the surfaces to be welded are in intimate contact throughout the welding cycle.

(3) *Heat Generation*: Heat is generated in the implant by absorption of the microwave radiation.

(4) *Heat Conduction and Melting*: The heat is conducted from the gasket to the thermoplastic parts, resulting in melting in the joint area. Material starts to flow and a weld is formed due to intermolecular diffusion and chain entanglement as the parts come into intimate contact.

(5) *Cooling*: The microwave power is terminated and the weld interface and bulk material are allowed to cool and solidify.

Pressure can be applied either throughout the process or just in the cooling stage, to obtain maximum heating and minimize the amount of material squeezed out of the joint [1, 2].

There are two different modes of microwave application: multimode and single-mode. Multimode microwave application is the system that is used in a conventional domestic microwave oven. The microwave field in the welding chamber (oven) is very complex, and depends on the absorbing material inside. The advantage of a multimode field is that it can provide relatively uniform volumetric heating, especially if it is moderated in time by using stirrers inside the chamber. However, the heating times can be relatively long.

In the single-mode system the heating cavity has specific dimensions in order to produce a well defined traveling- or standing-wave inside. This makes it possible to position the implant at the location of maximum field in order to produce localized heating.

15.2 Advantages and Disadvantages

Microwave welding is a relatively new process amongst welding techniques. The method offers a number of potential advantages including: short heating times due to volumetric heating, which is independent from thermal conduction; the possibility of complex and three-dimensional joint geometries; a reduction in capital cost of equipment, particularly for welding complex components; very low power consumption, and ease of disassembly. Additionally, the higher frequency used can result in faster heating than in radio frequency welding.

The disadvantages of microwave welding include: a consumable microwave susceptible material is normally required at the joint interface, which requires an additional stage in the welding cycle and has recycling issues; and materials containing polar molecular groups can heat up rapidly, causing material degradation if the heating rate and power level are not adequately controlled [3, 4].

15.3 Applications

The possibility of creating a two- or three-dimensional weld will potentially allow designers considerable freedom to generate thermoplastic components of increasing complexity. However, to date, the only published commercial application for microwave welding is the joining of PVDF pipes and fittings [5].

15.4 Materials

Any material that contains polar groups in its molecular structure can absorb microwave radiation. Polar plastics with high degrees of branching are more suitable than plastics with linear chains. For nonpolar thermoplastics, a microwave absorbing implant is required.

The most widely used implant material for microwave welding of plastics is polyaniline (PANI). Similar to semiconductors, PANI conducts electricity through doping with an aqueous acid such as HCl. Doping with dilute aqueous acid introduces polar groups into the molecular structure and makes the material electrically conductive by providing free-moving electrons. The amount of heat produced during welding is dependent on the conductivity. If the material is not conductive enough, the mobility of free charges is low, and very little heating occurs. If conductivity is too high, microwave energy is reflected, rather than absorbed, so that no heating occurs.

The electrical conductivity of PANI can be varied from that of an insulator (10^{-10} S/cm) to that of a conductor (10^4 S/cm), depending on the doping level and also how it is made; for example, stretched films have a higher conductivity than unstretched films and pellets. The conductivity of PANI also changes with temperature, and during storage [1].

Gasket implants are normally made by mixing acid-doped PANI powder with the thermoplastic material and compression molding a sheet. However, heat introduced during compression molding vaporizes some of the acid in the PANI powder, resulting in a loss of dopant. The conductivity of the gasket is therefore much lower than that of the PANI powder, and microwave absorption by the gasket is reduced.

15.5 Equipment

For both multimode and single-mode systems, the microwave field is generated by a cavity magnetron (Fig. 15.1), which consists of a hollow cylindrical chamber, the anode, containing a number of lobes, or resonance cavities. In the centre of the magnetron is the cathode, which is a hot filament at high negative potential. A magnetic field is applied parallel to the axis of the cathode, which causes the electrons, released from the heated cathode and attracted towards the anode, to spiral outward in a circular path. As the electrons sweep past the openings of the resonating cavities, they induce a resonant microwave field inside. A portion of this field is extracted to a waveguide, which directs the microwave energy to the welding chamber.

An example of a multimode microwave welding machine is shown in Fig. 15.2. Welding pressure is applied via a rod attached to a pneumatic cylinder, which passes through the top of the chamber. Since this hole can result in a leakage of microwave energy out of the chamber, it is important that it is designed correctly.

A single-mode microwave welding system is shown in Fig. 15.3. The power generator is connected to a three-port regulator, which prevents reflected waves from damaging the power source. A tuning screw matches the impedance between the source and the load, and a dual power meter located between the circulator and tuner monitors forward and reflected power. Welding is performed in the double-slotted applicator connected to the tuner. A dummy load connected to the applicator converts transmitted energy into heat; water is used for cooling. This system produces a traveling wave pattern in the applicator.

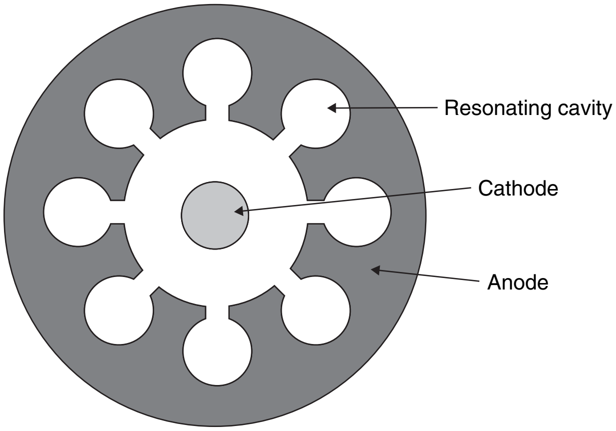

Figure 15.1. Cross-sectional diagram of a typical magnetron cavity (Source: TWI Ltd).

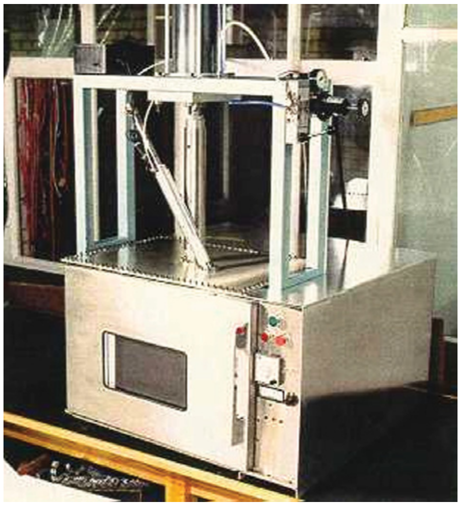

Figure 15.2. Multimode microwave welding machine (Source: TWI Ltd).

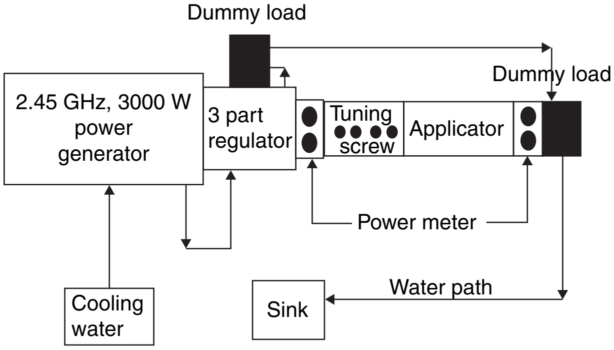

Figure 15.3. Schematic representation of a single-mode microwave welding machine (Source: Ref. [1]).

For generation of a standing wave pattern, the second power meter and dummy load are replaced by a solid plate to reflect generated waves. A standing wave pattern in a single mode microwave system produces a much higher field strength than a traveling wave pattern, as a result of constructive interference of transmitted and reflected waves.

For welding materials containing polar molecular groups, control of power output can be achieved using a digital-to-analog data acquisition board for voltage control. Pressure can be applied during welding using a solenoid valve, air cylinder, and relay [1–3].

Any fixtures for holding the parts during welding must be designed either to fully reflect, or transmit the microwave radiation so that they do not heat during the welding cycle. Normally these fixtures are made from nonpolar plastics, such as PTFE or PEEK.

15.6 Welding Parameters

Important welding/process parameters in microwave welding are typically the heating time, power level, welding pressure, and percentage of conductive polymer in the implant. These parameters affect the amount of heat generated, and the weld strength.

Increasing the concentration of conductive polymer in the implant and also the thickness of the implant increases the heating rate and joint interface temperature. Higher power levels also result in higher temperatures, faster heating rates, and decreased welding times. Heating time should be carefully controlled in microwave welding; at high power levels, temperatures at the joint interface can exceed 200°C (392°F) in less than 5 seconds. In materials containing polar groups, such as nylon, high power levels or long heating times may lead to overheating and material degradation.

In single-mode systems, absorption of microwave energy is influenced by the orientation of the implant in the microwave field; implants with the length placed parallel to the electric field display higher heating rates than implants placed perpendicular to the field, due to a greater tangential surface [2, 3].

In addition to effects on joint strength, squeezing out of implant material affects recycling considerations. Disassembling the weld is easier if more implant material is present in the weld interface when welding is completed. Since joint strength increases as more implant material is squeezed out, an optimal amount of gasket material remaining in the weld must be determined if disassembly and recycling considerations are important. Conductivity of the implant can also decrease upon reheating [3, 6].

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16 Solvent Welding

16.1 Process Description

Solvent welding and solvent cementing are often regarded as the same process, and they share many characteristics. However, they are distinguished in the following manner. Solvent welding refers to a process in which a solvent or solvent blend with no dissolved polymer is used to create a joint between two thermoplastic parts. Solvent cementing refers to a process in which the solvent or solvent blend used to create the joint contains dissolved polymer.

In both cases, the process exploits the reduction in glass transition temperature (T_g) of a thermoplastic polymer caused by the absorption of the solvent. The solvent softens the parts being welded, allowing increased freedom of movement of the polymer chains. Solvent applied to a noncross-linked polymer separates the polymer chains as if they were in solution. In a cross-linked polymer, however, the chains do not separate; the spacing between the chains increases and swelling of the polymer occurs. When two solvent-softened parts are pressed together, molecules from each part come into contact. As with all thermoplastic welding processes, the creation of a permanent joint depends on the application of time, temperature, and pressure to allow interdiffusion of polymer chains from one side of the joint to the other. The application of a suitable solvent reduces the temperature required to produce a weld, frequently allowing welding to be carried out at room temperature. Over a period of time, which may be up to several days, the solvent diffuses away from the joint (desorption), and the T_g of the polymer at the joint increases again, creating a permanent weld, with the continuity of the material across the joint. Solvent welding does not add any material to the joint, apart from a small amount of residual solvent. Solvent cementing adds polymer material to the joint, making it more suitable for processes where the part fit-up is poor, or gap filling is required.

A joint prepared using solvent welding or solvent cementing can only be repositioned for a short time after assembly, and cannot be dismantled for reworking. It is therefore important to check the part fit prior to joining, to ensure that the joint can be assembled easily. Self-locating features in the molding can be advantageous. The joint surfaces should be cleaned and dried before assembly, using a reagent that does not dissolve the polymer.

The solvent should be applied to the joint region of both substrates. This can be either a manual or an automated operation, using a brush, wipe, dip, pad, or capillary dispenser. If solvent cement is being used, then it may be necessary to apply a primer to each surface before applying the cement. The primer will typically consist of one or more of the solvents used in the cement, and is used to wet out the surface and to initiate diffusion of the solvent into the substrate.

The substrates are left for a short time to allow excess solvent to evaporate, and to allow the solvent to diffuse into the surface of the polymer. This typically occurs to a depth of 50–500 μm (0.002–0.02 inches), producing a solvent-affected zone (SAZ) on either side of the weld. The substrates are pressed together and held in place for a time between a few seconds and a few minutes. The applied pressure can then be removed and the assembled part is left for a longer period, between several minutes and several days, to allow desorption of the solvent. Some residual solvent usually remains in the SAZ, reducing the properties of the polymer in the region of the joint.

Solvents evaporate at different rates, depending on their boiling points. Some solvents evaporate so quickly that the lowering of the surface temperature results in the formation of condensation at the joint, commonly called “blushing”. To avoid this, a slower evaporating solvent, such as methylene chloride, is added.

For joining of PVC pipes using solvent cement, the following steps have been recommended as a practical guide [1].

(1) Ensure that the pipe ends are cut square.
(2) Deburr and chamfer the pipe ends.
(3) Assemble the joint in a “dry-fit” operation and make a depth-of-entry mark.
(4) Preclean the parts using a suitable reagent that does not dissolve the polymer.
(5) Apply the primer to both surfaces.
(6) While the surfaces are still wet, apply the solvent cement to both surfaces.
(7) Put a second application of cement on the pipe—enough to form a small bead when the

pipe is inserted in the fitting. The joint should be left open for a short time before assembly, to allow time for diffusion of the solvent into the substrate and for excess solvent to evaporate.

(8) Insert the pipe into the fitting with a quarter-turn rotation to spread the cement evenly, then hold the joint in place for 30–180 seconds.

(9) Wipe off excess cement.

(10) Leave the joint for at least 24 hours before pressure testing.

16.2 Advantages and Disadvantages

Solvent welding and solvent cementing are simple and inexpensive processes that can produce durable, hermetic joints. Compared with mechanical fastening, the joint may be lighter in weight, does not need additional components (yielding cost savings), and can be quicker to assemble (giving lower labor costs). The solvent processes also avoid the stress concentrations usually found at mechanical fastenings. Both processes can give a joint with low or zero visibility, and unlike adhesive bonding, there is no additional phase at the joint. A wide range of joint designs can be used and, compared with most thermoplastic welding techniques, these processes can be used to assemble relatively large components containing irregular joints. Solvent welding and solvent cementing can produce welds with very little or no weld flash, giving a better appearance than the welding techniques that use heat or friction, and, compared with frictional techniques, there is no risk of producing particulate debris.

Solvent welding and cementing are, however, not applicable to thermoset polymers, or to highly crystalline thermoplastic polymers. As with all plastics welding techniques, the processes are limited to joining compatible polymers. However, some dissimilar combinations are possible, for example PVC to acrylics or polycarbonate [2].

Residual solvent can reduce the strength of the polymer in an SAZ up to 0.5 mm (0.02 inches) wide on each side of the weld. Minimizing this reduction can require a long period of desorption to allow the solvent to diffuse from the joint. This can require a large inventory of work in progress.

If molded parts contain residual stresses, then there is a risk of solvent cracking or crazing when the solvent or cement is applied. Where possible, regions of high residual stress, such as an injection molding gate should therefore be positioned away from the joint. Annealing the parts before assembly can reduce residual stresses, but can also lead to part distortion, worsening the part fit-up. The polymers most vulnerable to stress cracking are PC, PS, acrylics, ABS, polysulfone (PSO), and polyphenylene oxide (PPO). The solvents most likely to cause stress cracking are esters, ketones, and aromatic hydrocarbons [3, 4].

Solvent welding requires good part fit-up and application of clamping pressure, because the thin layer of solvent is not capable of gap filling. Solvent cements have a higher viscosity than the solvent blends used for solvent welding, and can be used for applications where gap filling is required. However, it should be noted that significant shrinkage of the cement will occur when solvent desorption from the joint takes place, which can introduce internal stresses and voids.

The solvents used generally are organic, volatile, and sometimes inflammable and toxic. Although efforts have been made to find alternative solvents that maintain the benefits of the processes, these have not been successful [5].

16.3 Applications

Solvent welding is used for assembly of toys and for tamper-proof housings, for example, for utility meters.

Solvent cementing is widely used for assembly of pipes, for example, PVC pipes in plumbing applications, or ABS pipes for chemical plant.

Other applications include fabrication of hermetic seals in medical devices, and assembly of joints in applications where the final appearance is important, such as acrylic or polycarbonate display cases and isolation glove-boxes.

16.4 Materials

Solvent welding and solvent cementing can be used to join a wide range of amorphous and partially crystalline thermoplastics. Polymers with low molecular weight are, in general, more easily dissolved. Polymers dissolve most readily in solvents with similar polarity—polar polymers in polar solvents and nonpolar polymers in nonpolar solvents. The solubility parameter is commonly used to characterize polarity, with good compatibility between the polymer and solvent being most likely if the difference in their solubility parameters is less than 0.5. Some typical combinations of solvent and polymer are given in Table 16.1. If the solubility parameters of two polymers both match that of

Table 16.1. Suitable Solvents for Solvent Welding Various Plastics [6]

Plastic	Solvent														
	Acetone	Cyclohexanone	*N*,*N*-Dimethyl formamide	Ethyl acetate	Dichloroethane	Dichloromethane	Glacial acetic acid	Methyl ethyl ketone	2-Methoxy ethanol	*N*-Methyl pyrrolidone	*O*-Dichlorobenzol	Tetrachloroethylene	Tetrahydrofuran	Toluene	Xylene
ABS					■	■		■				■			
Acrylic					■	■	■								
Cellulose acetate	■			■				■	■						
Polyaryl ether	■			■											
Polyaryl sulfone			■							■	■				
Polycarbonate				■			■		■						
Polystyrene		■		■		■	■	■	■	■	■			■	■
Polysulfone		■			■	■		■			■	■		■	■
PVC	■	■							■		■		■		
PPO					■	■									
Styrene-acrylonitrile	■						■			■	■				
Vinylidene chloride		■	■						■	■					
Polyamide	Formic acid, phenol, resorcinol or cresol in aqueous or alcoholic solutions, calcium chloride in alcoholic solution														

the solvent, then it may be feasible to join these dissimilar materials. Testing of the process is recommended. Mixtures of solvents may also be used to increase compatibility.

A wide range of proprietary solvent cements is available. These consist of a solution of the polymer to be joined dissolved in a mixture of solvents. If a primer is required, then this will usually consist of one or more of the solvents in the cement. The cements are prone to gelation and have a limited storage life. It may be possible to restore cement that has started to gel, by adding a small amount of solvent and mixing. However this risks producing inconsistent joints, either because of inadequate mixing or because of an incorrect balance of solvents.

16.5 Equipment

Little equipment is required for solvent welding or solvent cementing. Solvents or cements are usually applied using brushes, wipes, or dispensers. Suitable personal protective equipment is required, as specified by the suppliers' instructions and safety data sheets. Adequate ventilation is also essential to ensure extraction of solvent fumes from the work area. Depending on production volumes, it may also be necessary to consider the capturing of volatile organic solvents to avoid their emission to the atmosphere.

High-volume production using solvent welding or cementing can use automated equipment for application of the solvent and assembly of the part. This could include an automated dispenser, which might be as simple as a cam-follower, or as complex as a multiaxis robot, followed by manual or automated assembly.

16.6 Application Methods

There is a wide range of methods available for applying solvents or solvent cements, including sprays, rollers, brushes, and wipes. However, two other methods are also commonly used: capillary application and dipping (or soaking).

16.6.1 Capillary Method

This method uses the ability of a low viscosity solvent to flow through a joint area by capillary action. It is mainly used for smaller parts and fairly short bond lengths. The solvent is normally applied using a cannula-tipped bottle or hypodermic needle. With this technique, it is important that the parts fit together without leaving any visible gaps. The solvent should be applied evenly along the entire length of the joint.

16.6.2 Dip or Soak Method

In this method, as the name suggests, the parts are dipped into a tray containing the solvent. It is important that only the edges to be joined are dipped; exposing too much area to the solvent will result in a weak, slow setting joint and will also affect the appearance of the part. This can be controlled by masking the area around the joint using tape or masking compounds. The edges of the parts can be supported on pins or wires to ensure that the solvent can get underneath. Parts are dipped for normally between 20 and 30 seconds, depending on the wall thickness, before being brought together.

The main drawback with this technique is that it uses open trays of solvent, and therefore requires fume extraction.

16.7 Joint Design

A wide variety of joint designs, illustrated in Fig. 16.1, are available for solvent welding or cementing. The load-bearing capacity of a joint can generally be increased by increasing the joint area. The wall

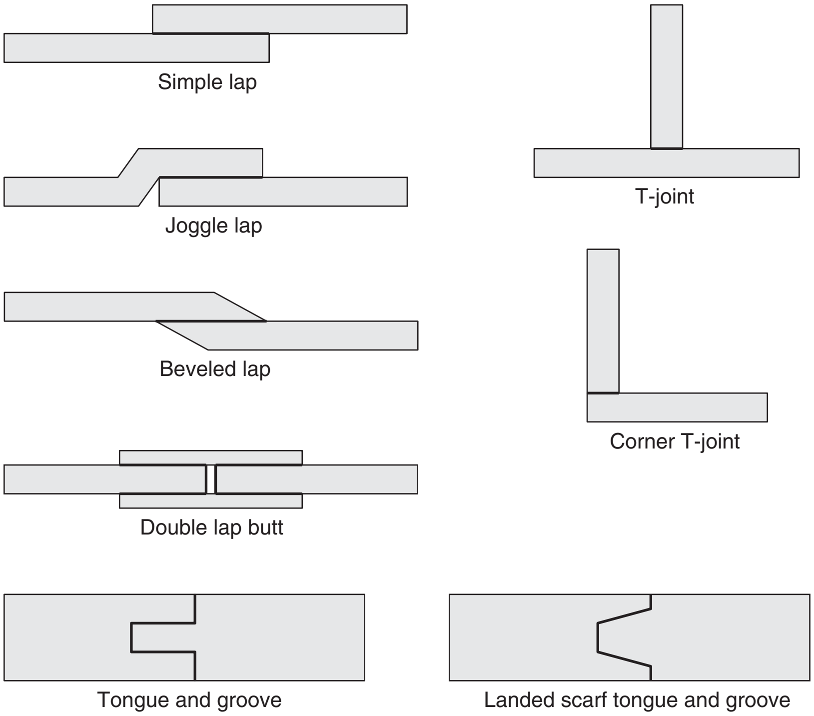

Figure 16.1. Joint designs for solvent welding and solvent cementing (Source: TWI Ltd).

thickness limits the joint area for T-joints, corner joints, and butt joints, so these joints are not recommended for these processes.

Solvent welding is not suitable for joints where gap filling is required, or where it is impossible to apply clamping pressure. In these cases solvent cementing may be a better option.

16.8 Welding Parameters

Solvent welding and solvent cementing are both robust processes. However, if too little or too much solvent is applied, then this can result in a poor weld. If excess solvent is applied to a joint, then this can be allowed to evaporate before assembly. Enough time is needed during solvent application for the solvent to diffuse into the polymer surface, and for the excess solvent to evaporate. Substrates may be preheated, which ensures that the surface is dry, and can accelerate diffusion of the solvent into the surface. However, if the surface is too hot then the solvent will simply flash off before the joint can be assembled.

Good part fit-up and smooth joint faces can help produce a sound weld. A high clamping pressure and long welding time can also help to produce a strong weld, particularly if the fit of the parts is poor, or the substrates are rough.

Application of heat or vacuum or both after assembly can accelerate desorption of the solvent, helping to reduce the level of residual solvent, and therefore minimizing the reduction in strength at the joint. However, this would add significantly to the cost of manufacture, so commercial processes use ambient temperature and pressure.

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17 Adhesive Bonding

17.1 Process Description

17.1.1 Introduction

Adhesive bonding is the most versatile of all joining techniques and can be used to join plastic parts to each other or to other materials such as metals, ceramics, or wood. A range of joint strengths is available, ranging from low-strength putty and caulking compounds, which are used only for space- and void-filling, to high-strength structural adhesives used in the automotive and aerospace industries.

In simplest terms, an adhesive is applied to the substrate, or adherend, surfaces; the joint is formed by holding the components together while the adhesive cures/hardens to develop structural properties, forming a bond to both surfaces.

17.1.2 Mechanism of Adhesive Bonding

In adhesive bonding, attractive forces form between the adhesive and the adherends. The type of attractive force varies with the type of adhesive and adherends, but is generally a combination of some or all of the following forces:

- Adsorptive: These forces result from intimate interaction between particles at the joint surface. Attachment of such particles (including atoms or molecules) can be through weak, dipolar, or Van der Waals interactions or through chemical, usually covalent, bonds.
- Electrostatic: These forces are due to ionic bonds between oppositely charged species or molecules.
- Diffusive: These forces result from molecular chain entanglements between the adherend and adhesive as they diffuse across the joint interface.

It is not always appreciated that attractive interfacial forces are very strong. Indeed, in many cases these forces are stronger than the cohesive forces of the adhesive or plastic adherend, and joint failure generally occurs in the adhesive or adherend, rather than at the joint interface.

Additionally, interfacial bond strength is enhanced through the effect of larger scale micro and macro surface effects (through etching, roughening, abrasion, etc) resulting in mechanical interlocking and frictional forces [1, 2].

17.1.3 Interface Processes and the Role of Surface Preparation in Bonding

For adhesion to take place, it is necessary for wetting to occur between the adhesive and the adherend. Wetting, which relates to the spreading out of a liquid on a solid surface, is achieved when the surface tension of the liquid adhesive is lower than the surface tension (or energy) of the adherend. Due to internal, or cohesive, forces (forces of attraction between molecules within the material) liquids tend to adopt shapes that minimize their surface area. When droplets of liquids with high-surface tensions come into contact with a substrate of a lower surface energy, they will tend to adopt a more spherical shape, while droplets of liquids with lower surface tensions tend to flatten out on the solid surface where the surface energy is sufficient to bring a larger area of the liquid into contact with the surface. Organic solvents have low surface tensions and they wet surfaces more easily than water which has a high surface tension. If the surface tension of the adhesive is too high, it will form a round droplet on the adherend surface, similar to the beading of water on a waxed car, instead of spreading out over the surface (Fig. 17.1). Representative values for various common adhesives and adherends and liquids are given in Table 17.1. Good surface wettability is achieved when the contact angle between the substrate and adhesive droplet is less than 60°; poor surface wettability occurs with contact angles greater than 90°. Whilst the surface energy of each adherend is intrinsically linked to its material/chemical composition, use of appropriate surface preparation techniques can compensate for poor wetting [2–5].

According to the boundary layer theory of adhesive joint strength, macromolecules of adsorbed adhesive form an interfacial boundary layer with molecular properties different from those of the bulk adhesive. Strong joints occur when this interfacial layer is strong enough to withstand external stresses. Weak joints result from weak boundary layers that contain entrapped air, impurities, or weak surface chemical layers on the adherend. The boundary layer contains oriented domains of adhesive polymer molecular groups called attachment sites; a greater number of attachment sites results in

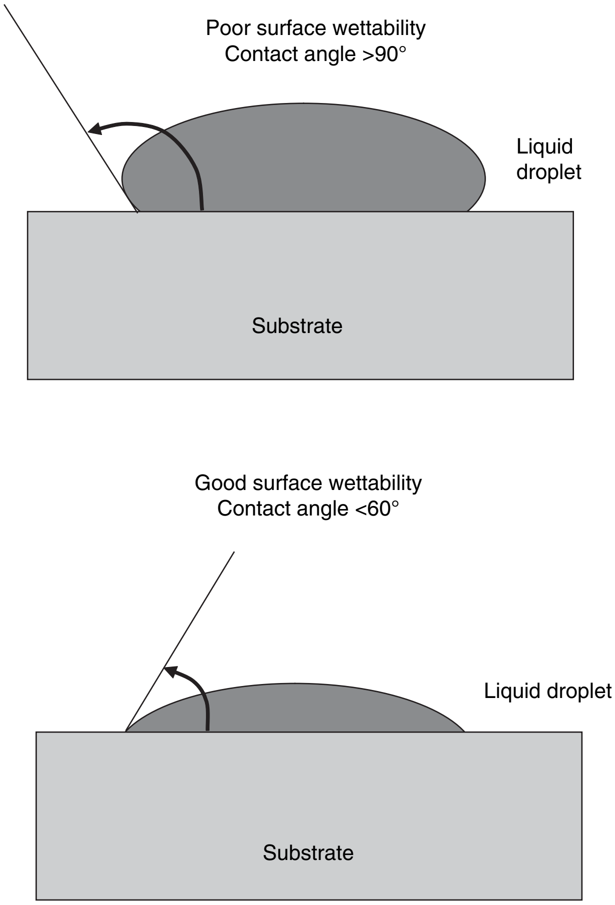


Figure 17.1. Surface wettability (Source: TWI Ltd).

greater joint strength. Conversely, environmental deterioration of joint strength results from the destruction of attachment sites [1, 2].

Since adhesive bonding is mainly a chemical joining process that occurs on the surface, the success of the process is primarily dependent on surface preparation of the adherends and the techniques used for handling, applying, and curing the adhesive. Appropriate surface preparation of the joint is necessary for optimum attraction and joint strength. Adherend surfaces may need to be roughened to increase surface area and create points of mechanical interlock and be free of contaminants that would interfere with the forces of attraction [2].

17.2 Advantages and Disadvantages

17.2.1 Advantages

Adhesive bonding is an efficient, economical, and durable method for assembling plastics to plastics or to metals, wood, ceramics, or other materials. It is the most versatile joining method, capable of joining almost all types of plastics in contrast to welding and fastening where particular processes may be limited due to specific material properties, applications, or geometries. It can be used for joining films, sheets, fabrics, particles, and substrates with unusual shapes or physical configurations, such as sandwich panels, and honeycomb cores for aerospace applications, laminated wooden beams, grinding wheels, sandpaper, laminated films, cardboard boxes, and flocked wallpaper can be adhesively bonded. It can be used for difficult-to-fasten materials, such as fastening films and fabrics to solid substrates. A property called tackiness or grab in some adhesives before curing helps to hold components in place until curing is completed. It is a permanent assembly method and produces a continuous, almost uniform seal, which is virtually impervious to gases and liquids. It is an aesthetically pleasing joining

Table 17.1. Representative Values of Surface Tension/Surface Energy for Various Materials

Materials	Surface tension (energy)	
	dyne/cm	mJ/m^2
Fluoroethylene propylene	16	0.016
Polytetrafluoroethylene	18	0.018
Silicone	24	0.024
Ethylene-propylene rubber	28	0.028
Polyethylene	31	0.031
Polystyrene	33	0.033
Styrene-butadiene rubber	33	0.033
Acrylonitrile butadiene styrene	35	0.035
Acrylonitrile-butadiene rubber	37	0.037
Polyphenylene sulfide	38	0.038
Polymethylmethacrylate	39	0.039
Polyvinyl chloride	39	0.039
Polyimide	40	0.040
Polysulfone	41	0.041
Polyethylene terephthalate	43	0.043
Cellulose	45	0.045
Polyamide	46	0.046
Polycarbonate	46	0.046
Acetal	47	0.047
Epoxy	47	0.047
Water	73	0.073
Aluminum	~500	~0.500
Copper	~1000	~1.000

process, since no fasteners are visible and, because the adhesive covers the entire joint surface, stress is distributed over a large area. In addition, adhesively bonded joints have high levels of fatigue tolerance, often much higher than any other joining method [1–3, 6].

Adhesives possess a range of physical properties, allowing the selection of a suitable material for each particular application. Joint properties, such as expansion and contraction, can be tailored to application requirements. Adhesives are normally electrically insulating materials and minimize the corrosion of metals by interrupting the cathodic effect. They are lightweight (1.1–1.2 g/cm^3 or 0.007 lb/in^3 for unfilled adhesives), and a thin bond line (0.05–1 mm; 0.002–0.04 inches) adds little weight to the assembly. Adhesives are easily applied with automated systems and can be used to augment mechanical assembly [1, 6, 7].

Adhesive bonding has many advantages over mechanical fastening. It is lightweight and does not require any extra components, resulting in cost savings and reduced labor for processing. In mechanical fastening, holes often must be machined into the part, creating points of stress in the plastic that can lead to cracking and distortion; joint failure occurs rapidly when mechanical fastening is used to join to ceramics or glass. In mechanical fastening, the applied load is concentrated at the fastener location. Adhesive bonding spreads stresses out over the entire bond area, and contour irregularities produced by bolts and rivets are not present. In addition, part design in mechanical fastening must accommodate bosses and holes, and aesthetic appearance of the final assembly is impaired. Adhesive bonding can provide bonds in irregularly shaped parts where bosses cannot be used [1, 3, 8].

Advantages over welding include the ability to bond thermoplastics to thermosets, metals, glass, and other materials. Dissimilar thermoplastics joined using welding must be chemically compatible, with similar melting characteristics; any thermoplastics can be joined with adhesive bonding. Joints using ultrasonic welding are restricted in geometry; a large variety of joint designs, including those with irregular bond lines, is possible with adhesive bonding. Welding often requires expensive equipment and tooling, while only simple equipment is needed for adhesive bonding [3].

Adhesive bonding has several advantages over solvent bonding. Solvent bonding cannot be used to bond thermosets or materials such as metal or glass. Solvents cannot be used for parts with large gaps, and they are more likely than adhesives to cause stress cracking [3].

17.2.2 Disadvantages

Disadvantages include limited shelf lives and working lives of some adhesives, rigorous surface preparation, and sometimes lengthy cure times. Adhesive application can be messy, requiring extensive clean-up, and hazardous vapors may be given off during curing. Sufficient bond area is necessary for optimum strength, and bond integrity cannot be inspected easily. Stress cracking can occur from a reaction between the polymer and particular adhesives, normally prior to or during curing [2].

Adhesives, like polymers, have a limited temperature range over which they are useful; oxidative degradation can occur at high temperatures, and some adhesives become brittle at low temperatures. Where volatile solvents form part of the adhesive system, flammability can be a problem, however this is less of an issue these days due to a continuing move away from solvent-based systems to either water-based or 100% solid systems.

Adhesives and application tools can appear to be expensive when considered in isolation, and disassembly is usually not possible without destruction of the component parts [1, 2, 8].

17.3 Applications

Adhesive bonding can be used to join different types of plastics and composites to themselves and to other materials, such as metals, wood, fabric, film, or cardboard. With a clean substrate surface, most materials can be adhesively bonded to a similar or dissimilar material; for difficult materials (e.g., those with a low surface energy such as PE, PP, or PTFE), primers, or special surface preparation techniques can increase bondability significantly. Substrates can take any form including blocks, films, sheets, particles, sandwich structures, or honeycomb cores.

Applications where polymers are joined using adhesives are incredibly varied and include the following:

- *Cosmetic Containers*: Many attractive polymeric materials can be used to great effect when joined to form receptacles and similar items, adhesive bonding is often the most effective, economical and aesthetic way to achieve this.
- *Lighting*: Adhesives are often used to manufacture plastic lighting structures, including low power systems (e.g., LED, LEP, and electroluminescent systems).

- *Optical Components*: The increasing use of high refractive index polymers (PMMA, PC, and nylon) in items such as glasses, cameras, photonics, etc., has necessitated the development of a range of ultraviolet (UV)-curing adhesives to enable the joining of such materials so that movement and misalignment are minimized.
- *Sporting Goods*: Virtually all items used for sport will contain some level of adhesive bonding, whether it be to bond the rubber surface of a table tennis bat to the highly complex laminated construction required by skis and associated boards (surf, snow, kite, sail, etc.). Many high quality bicycles (mountain and road) are constructed from a mixture of metal and polymer composite materials which can be joined only using adhesive technology.
- *Office Equipment*: Adhesives are used within office electronics, for example, to attach and retain components on circuit boards, and to attach fabric on furniture.
- *Toys*: Whether constructed of natural polymeric materials (e.g., wood and leather) or synthetic thermoset/thermoplastics, adhesive bonding forms an intrinsic method of assembly, in particular due to its ability to join dissimilar materials and avoid the use of fasteners, which can present a safety risk should a component become detached.

Structural adhesives are used in the aerospace, automotive, sport, and appliance industries for joining structural components. Adhesives are used in assembling medical components, such as orthopedic braces, hearing aids, transducers, infusion devices and pumps, medical electronic equipment, catheters, and attaching stainless steel hypodermic needles to plastic housings. Adhesive applications also include threadlocking, thread sealing, retaining, and gasketing [9, 10].

Automotive applications include bonding two-piece thermoplastic bumpers and rearview mirrors bonded to glass windshields. In addition, the attachment of trim is almost entirely done using adhesives ranging from double-sided structural tape through to polyurethanes and cyanoacrylates. The benefits of using adhesives include the avoidance of producing holes, more rapid assembly, tolerance compensation, and aesthetic benefits [10–12].

The joining of polymer composite materials (continuous fiber reinforced materials and honeycomb sandwich structures) has always presented challenges to the engineer. For though these materials offer significant advantages over conventional materials in terms of weight saving, performance, and durability, their inherent structure (anisotropic laminate) makes the joining of these materials to others difficult. Although mechanical fastening is used, the anisotropic laminate structure is sensitive to any form of defect or damage such as holes, resulting in local stressed areas and a degradation in the overall performance. The most favorable approach therefore is to employ adhesive bonding, where the load can be evenly spread over a large area. There are many examples where this has been applied with great success, including bonding of composite pipework, the joining of ship hulls (steel) to the upper composite superstructure, and in the joining of sandwich structures for the automotive and aerospace industry. In all of these examples, different approaches in terms of joint design, material/process selection, and assembly mode have been taken to provide an effective bonding solution in each case [11].

Since the 1950s, adhesive joints have been used increasingly in shoe manufacturing as an alternative to sewing and other fastening techniques, indeed within the leisure sector (trainers, etc.), joining is almost exclusively adhesive-based. The primary materials used include leather, canvas, textiles, nylon, and PVC for the uppers, and leather, rubber, EVA, PVC and polyurethanes for the soles. Depending on the material combination and the area of shoe to be joined, a number of adhesive types are used, the majority based on rubbers, hot-melts, or polyurethanes. More detail is provided in Table 17.2 [11].

A particularly innovative approach to adhesive bonding of thermoplastics is for the production of musical stringed instruments, such as acoustic guitars (Fig. 17.2) where the wooden structure is replaced by

Table 17.2. Adhesives Used in Shoe Bonding

Shoe Joining Area	Adhesive
Mounting	Cement (rubber adhesive)
Heel covering	Polyurethane
Heel attachment to sole	Polyester hot-melt
Box toe bonding	Polyamide hot-melt
Shank and cushion bonding	Waterborne polyurethane
Lift attachment	Polyester hot-melt
Sticking of socks lining	Polychloroprene
Upper to sole bonding	Polyurethane, polychloroprene

Figure 17.2. An all-polymer guitar, completely assembled using adhesives (Source: Cool Acoustics).

plastic. Foamed polycarbonate sheet is used for the soundboard, bonded directly to a molded polyurethane body with thermoplastic carbon composite in areas where stiffening is required, such as the neck area. Due to the different surface sensitivities associated with the various polymers used, a room temperature curing epoxy adhesive was selected for all joining operations.

17.4 Curing of Thermosetting Adhesives

Cure time and method are important in obtaining optimum joint strength. Although the classical definition of curing a resin refers to the chemical cross-linking of a thermosetting polymer, a broader definition is used for the curing of adhesives. Adhesive curing generally refers to the process in which a polymer undergoes a change from the liquid to the solid (gel, rubber, or hard plastic) rheological state, regardless of the physical or chemical method used to induce the change. The method used to induce the liquid-to-solid conversion depends on the class of adhesive. For a thermoplastic adhesive, curing is the physiochemical process of cooling the molten polymer. Other curing processes involve chemical reactions; thermosetting adhesives (epoxies, polyurethanes) are cured through chemical cross-linking, while other adhesives, such as cyanoacrylates, cure by polymerization of a liquid monomer [1, 2].

A number of techniques exist to monitor the curing of thermosetting adhesives including thermomechanical analysis, thermogravimetric analysis, differential scanning calorimetry and torsional braid analysis. The phase diagram in Fig. 17.3 describes the rheological states of a thermoset polymer during the cure process. For example, a liquid epoxy adhesive can be cured by an anionic cross-linking mechanism using a basic polyamine. Allowing the reactive mixture to cool to the crystallization temperature (TCM) or the glass transition temperature of the precured adhesive (Tgm) would result in either very slow curing, or none at all. At temperatures above Tg, the reactive mixture is in a liquid state, and cross-linking can occur within a finite period of time. At a typical isothermal cure temperature (TA) below the glass transition temperature of the cured adhesive, the liquid would first progress through a gel phase, followed by a rubber phase, and end the cure as a polymeric glass. A high degree of cross-linking is achieved in the glassy state, the optimum final cure state for structural adhesives. If cured isothermally above the glass transition temperature of the cured adhesive (TR), only a gel phase would precede the final rubber phase; a glassy state would not be reached. If cured above the thermal degradation temperature of the adhesive (Tu), polymer degradation would result in poor cross-linking and joint strength. Theoretically,

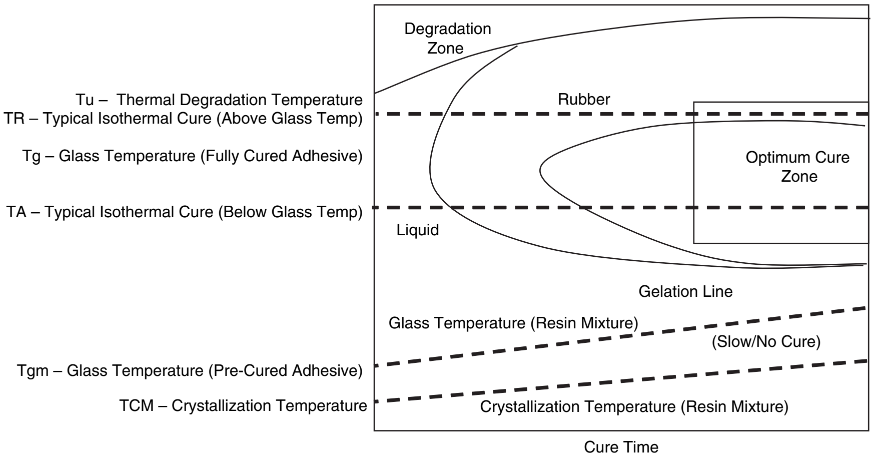


Figure 17.3. A phase diagram showing the rheological states of a model thermosetting polymer during the cure process (Source: TWI Ltd).

each thermosetting adhesive has a characteristic time/temperature profile; however, cure profiles of many adhesives are not known [1].

Some adhesives cure by exposure to high temperatures; however, curing agents or initiators are usually necessary to begin polymerization or cross-linking reactions. Many adhesives cure by reaction with weak bases or anionic functional groups (water, amines, anhydrides, amides). Some require initiators, such as peroxides, oxygen, ultraviolet light, or electron beams, in order to generate free radicals for a polymerization chain reaction. Other adhesives require metal salts, acids, or sulfur for cure reactions. Cure times can range from a few seconds to several days [2].

17.5 Classification of Adhesives

Adhesive classification, at first sight, can appear quite confusing due to the range of ways in which such materials can be described, the main ones being [2]:

- Chemical type
- Physical form
- Cure mechanism
- Function

17.5.1 Chemical Type

Materials used as adhesives can be divided broadly into three classes: (1) natural polymeric compounds, (2) inorganic materials, and (3) synthetic polymeric materials (thermoplastics, thermosets, elastomers).

Within each of these three classes, a range of chemistries can be defined:

- Natural polymeric—starches, dextrins, proteins, natural rubber, etc.
- Inorganic—silicones, silicates, etc.
- Synthetic polymeric—epoxies, acrylics, polyurethanes, etc.

17.5.2 Physical Form

Forms of adhesives include liquids, pastes, films, and foams. Within each form there may be a range of variations and it should also be mentioned that some forms will be thermally sensitive, especially liquids and pastes. As a subset within this class, adhesives are sometimes referred to by the number of components required for cure, that is, two-part or single-part system.

One particularly interesting physical form, termed thixotropic, has properties that allow it to behave like a low viscosity liquid when subjected to shear forces (e.g., painting or spreading) but to have gel-like properties once such forces have been removed. Thixotropic systems are used in a wide variety of applications where the adhesive must not flow or move under gravity once it has been placed in position.

Adhesives can be water-based (in which surfactants are used to disperse and stabilize polymer chains into small particles), solvent-based, or 100% solids.

17.5.3 Cure Mechanism

Adhesives can be classified according to cure mechanism, the main ones being:

- Chemically reactive—sometimes referred to as two-part systems and normally cure at room temperature, e.g., epoxy, toughened acrylic, etc.
- Moisture cure—usually single part adhesives, e.g., polyurethanes, silicones, etc.
- Anaerobic—which must cure in the absence of air, e.g., anaerobic acrylics.
- Hot melt—requires heat to melt the adhesive to become a liquid, e.g., polyamide (PA) based adhesives.
- Light cure—requires energy in the form of UV or near UV (blue) light, e.g., UV curing acrylics.
- Heat cure—requires some level of heat to cure, e.g., single component epoxy adhesives, which need temperatures greater than 120°C (248°F) to cure effectively.
- Pressure sensitive—although not strictly curing, in that the adhesive does not change form, pressure is required to "encourage" the adhesive layer to wet the adherend surface and thus form a higher strength bond.

17.5.4 Function

Functional classifications include holding adhesives, such as masking tape, which holds parts together for limited amounts of time; instant adhesives, which cure within seconds; structural adhesives, which can sustain stresses of at least 50% of the original strength of the part; one-part adhesives, such as rubber cement; and two-part adhesives, such as epoxies [2, 5].

17.6 Adhesive Types

Most commercial adhesives are classified according to polymer composition or chemical type. Major classes are described in the following sections.

17.6.1 Acrylics

Acrylic adhesives are derivatives of acrylic acid esters. They usually have short- or long-chain ester substituents or cyano groups, and may be a mixture of monomers and prepolymers. Long-chain acrylics, such as butyl methacrylate, are relatively soft; methyl methacrylate, with a short carbon chain, has a higher strength and modulus. Blends of short and long chains are also possible, allowing a wide range of flexibility in adhesive properties. Due to the range of chemistries involved, the acrylic family can be split into a number of subsets, the main ones being:

- Structural methacrylates
- Second generation or reactive acrylics
- Cyanoacrylates
- Light curing acrylics
- Anaerobic acrylics
- Toughened or static mix acrylics.

Substituted acrylics, such as the cyanoacrylates, are highly reactive and cure within seconds of application. Other acrylic adhesives, such as toughened acrylics, can dissolve grease and can wet contaminated surfaces. They are less sensitive to adherend surface preparation when compared to other adhesives, such as epoxies [13].

Curing occurs through polymerization, by free radical, or anionic mechanisms. Free radical polymerization, a chain reaction, can be initiated by organic peroxides or other active oxygen compounds or by UV light. Polymerization with peroxide initiators requires elevated temperatures (60–100°C; 140–212°F) in order to occur at a significant rate; activators and catalysts are necessary for polymerization at lower temperatures. Activators, such as reducing agents, induce peroxides to initiate the reaction, while catalysts or accelerators (tertiary amines, polyvalent metal salts) increase the polymerization rate. Acrylic polymerization can result in a large adhesive shrinkage during curing. To avoid the large cure stresses this shrinkage would generate, polymerized acrylic is commonly dissolved in acrylic monomer, resulting in a viscous solution in which shrinkage during polymerization is reduced. Inert filler material, such as silica, is also sometimes used. Cross-linking can occur in addition to polymerization, if a small amount of polyfunctional acrylic derivatives is present in the adhesive before curing [13].

Once initiated, polymerization proceeds to completion, forming a high molecular weight adhesive with a glass transition temperature that is independent of cure temperature. Temperature resistance of the polymerized acrylic is determined by the monomers and polymers present before curing and not by cure conditions. Maximum operating temperatures of some systems are usually around 105°C (221°F), the glass transition temperature of polymethyl methacrylate. Prolonged high temperature exposure may cause thermal depolymerization of these systems. However, many acrylics can be formulated to tolerate much higher temperatures, up to and exceeding 149°C (300°F); such systems often incorporate epoxy chemistries [13, 14].

17.6.1.1 Structural Methacrylates

Structural methacrylate adhesives are composed of elastomers and toughening agents dissolved in methyl methacrylate and other monomers. Cure is initiated by the addition of peroxide, which decomposes to form free radicals. Polymerization occurs at room temperature. Methacrylates are available in a range of cure speeds and exhibit superior low temperature impact performance. High strength bonds can be achieved with a variety of materials, especially plastics. Self-foaming formulations provide excellent gap filling but maintain the strength of unfoamed formulations. Methacrylates can be reprocessed with plastic parts for recycling; no separation is necessary. They blend with the thermoplastic melt during reprocessing, and the reprocessed plastics have similar mechanical properties to those without adhesive [12].

Advantages/disadvantages: Advantages include rapid cure, high joint strengths to plastics and the ability to be reprocessed for recycling. However, they have relatively low temperature performance and can cause possible stress cracking in some polymers.

17.6.1.2 Second-generation Acrylics

Second-generation acrylics, often termed reactive or no-mix acrylics, contain dissolved polymers to reduce shrinkage and increase toughness. They cure rapidly (<2 minutes at room temperature) by a free radical mechanism. They are two-part adhesives but require no prior mixing. Each adherend surface is coated with either adhesive or accelerator (often referred to as an activator), which diffuse together when the parts are mated. Diffusion mixing is possible up to a bond line gap of 0.5 mm (0.02 inches); with greater bond gaps, these adhesives must be mixed prior to application [13, 14].

Typically, these systems develop handling strength in about two minutes and full strength in 4–24 hours. The activator serves only as a catalyst for the polymerization of the resin, so the ratio of activator to resin is not critical. However, this is not the case for solventless activators, which are so concentrated that excess activator can prevent the adhesive from forming an intimate bond with the substrate. Since polymerization is initiated at the interface between the activator and resin, the cure depth is limited. Typically, the maximum cure-through depth is 0.76 mm (0.03 inches) from this interface [3].

The resin base of no-mix acrylic adhesives can also be heat-cured. A typical heat cure cycle is ten minutes at 149°C (300°F). Heat curing normally offers higher bond strengths and shorter cure times. However, heating the adhesive lowers the resin's viscosity and may result in some adhesive flow out of large gaps [2].

Advantages/disadvantages: Advantages include no requirements for mixing, rapid cure, good adhesion to plastics, room temperature cure, and the ability to accelerate cure with heat. Disadvantages include possible adverse effect on some solvent-sensitive plastics (stress cracking, marking, etc), unpleasant smell of uncured components, and limited cure-through depth.

17.6.1.3 Cyanoacrylates

Cyanoacrylate adhesives are colorless, one-part, room-temperature-curing adhesives that are available in viscosities ranging from water-thin liquids to thixotropic gels. When pressed into a thin film between two surfaces, cyanoacrylates cure rapidly to form rigid thermoplastics with excellent adhesion to most substrates (plastics, metals, rubber, wood, skin, etc.) [2, 3].

Highly reactive cyanoacrylic esters, such as methyl or ethyl cyanoacrylate, cure through anionic polymerization at room temperature, with trace amounts of water or amines as catalysts. Adherend surfaces generally contain sufficient amounts of absorbed water to catalyze polymerization, which is then completed in around 30 seconds for rubber and 1–2 minutes for metals and plastics. Fixture times for low viscosity adhesives are lower than for those with higher viscosity. Basic surfaces cure more rapidly than acidic surfaces, and only minimal shrinkage occurs during curing. The rapid curing of cyanoacrylates reduces or eliminates the need for clamps or holding fixtures. Joints made with cyanoacrylates are frequently stronger than the bulk material, especially with thin plastic substrates [1, 3, 7, 14].

General purpose cyanoacrylates form brittle joints with high shear and tensile strengths and can withstand temperatures from –54°C (–65°F) up to about 82°C (180°F) at low humidity, and indoors show no significant changes over a number of years. Minimal degradation is possible outdoors, depending on the substrate; however, exposure to severe temperatures, solvents (water, acetone, alkaline solutions), or weathering will produce bond weakening and eventual collapse. Generally, ethyl cyanoacrylate forms stronger, more durable joints to rubber and other flexible substrates; methyl cyanoacrylate adhesives produce slightly higher joint strengths with rigid plastics and metals [1, 3, 7, 14].

Although catalysts are not necessary for cyanoacrylate polymerization, they do provide more rapid curing. Curing is most rapid with thin bond lines; thicker gaps (0.5 mm; 0.02 inches) generally require higher viscosity cyanoacrylates and may require catalysts or activators to increase the cure rate. An amine catalyst can be applied to a joint surface before bonding. After the solvent has evaporated (usually 10–60 seconds), the adhesive is applied to the joint surface; catalyst activity after solvent evaporation ranges from 1 minute to 72 hours. Phenylethyl-ethanolamine is a common catalyst used in cyanoacrylate curing; however, it shortens joint life and does not promote the ability to cure between large gaps (gap curing). Other catalysts can be sprayed over a drop of free cyanoacrylate for curing, a method used for tacking wires or small components in electrical assemblies [1, 3, 7].

Cyanoacrylates can be used for bonding difficult-to-bond plastics such as fluoropolymers, acetal resins, and polyolefins, if primers are first applied to the adherend's surface. Primers, or adhesion promoters, are substances with chemical structures that promote strong adhesive properties (surface tension effects, dipole interactions) when applied in very thin films. They increase adhesion and improve shear, peel, and tensile strength. After evaporation of the primer solvent, the adhesive can be applied; depending on the type of plastic, joint strengths up to twenty times that of the unprimed joint strength can be obtained. Primers are normally active from four minutes to one hour after solvent evaporation [1, 3, 5, 7].

Cyanoacrylate formulations can be modified to produce joints with particular properties. Addition of rubber results in joints with high peel strength and impact resistance. Temperature-resistant cyanoacrylates retain bond strength even after exposure to 121°C (250°F) for thousands of hours. "Blooming" or "frosting", which can occur when general purpose cyanoacrylates volatize, react with moisture in the air and settle on the part, can be eliminated by using special "low-odor/low-bloom" cyanoacrylates with lower vapor pressures [3, 7].

The shelf life of uncured adhesive is about one year in polyethylene or metal containers; exposure to humidity and ultraviolet light shortens shelf life, while refrigeration extends it.

The life of the bonded article is usually less than five years. Special precautions should be observed when handling cyanoacrylates; one needs to consult the manufacturer for details [1].

Advantages/disadvantages: Advantages of cyanoacrylates include absence of solvents in their formulation, automated dispensing, rapid curing, the availability of multiple viscosities, and Class VI compliance for short-term (<29 days) medical device applications. Most cyanoacrylates are one-part systems that cure rapidly at room temperature and provide excellent shear and tensile strength. Disadvantages include joint brittleness, limited gap curing, poor peel strength, poor solvent and temperature resistance, and rapid bonding to skin. Certain polymers may exhibit stress cracking and/or blooming when bonded with cyanoacrylates [3, 7].

17.6.1.4 Light-curing Acrylics

Light-curing acrylics (including cyanoacrylates), composed of a blend of acrylic monomers, oligomers, and polymers, polymerize after exposure to UV light of a particular wavelength and intensity. They are one-part, solvent-free adhesives, available in a wide range of viscosities, from 50 centipoise (cP) to thixotropic gels. Photoinitiators added to the adhesive before bonding decompose under UV light to produce free radicals, which initiate polymerization of the acrylate groups to produce a thermosetting polymer. Cure times generally range from 2–60 seconds; cure depths can be as high as 13 mm (0.5 inches). Cured adhesives range from rigid, glassy materials to soft, flexible elastomers [7, 15].

When cured in the presence of air, free radicals can react with oxygen before initiating polymerization, leading to incomplete curing and a tacky surface. To minimize oxygen inhibition, light intensity can be increased, or the wavelength of light used can be matched to the absorbance of the photoinitiator. Alternatively, oxygen can be removed by flooding the adhesive surface with nitrogen during curing [7].

Advantages/disadvantages: Advantages of light curing acrylics include the ability to cure on demand, good environmental resistance, easily automated dispensing, clear bond lines, Class VI compliance (only for certain medical grades), and rapid fixtures. They are suitable for joining dissimilar materials or for joints with large gaps, and no volatile substances are formed during the cure. Disadvantages include oxygen inhibition of curing (tacky surfaces), initial expense for light source equipment, and the necessity of venting ozone produced by the light source. At least one substrate must be transparent so that light is able to reach the joint interface. Light-curing acrylics are commonly used to join vinyl and polycarbonate materials [7].

17.6.1.5 Anaerobic Adhesives

Anaerobic adhesives are one-part adhesives composed of dimethacrylate monomers (esters of alkylene glycols and acrylic or methacrylic acid) that cure only in the absence of air. They are less toxic than other acrylics, have a mild, inoffensive odor, and are not corrosive to metals. Anaerobic adhesives are stored in partially filled polyethylene containers, in which the ratio of air-exposed surface to volume is high. A range of viscosities are available, from four to several million centipoise, and the shelf life is greater than one year, depending on the amount of air in the container. Anaerobic adhesives can fill bond gaps from 0.025 mm (0.001 inches) to ~1 mm (0.04 inches) [1, 2, 14].

Anaerobic adhesives are used for structural bonds, primarily with materials such as metals and glass and to a lesser extent, wood and plastic (thermosets and some thermoplastics). An activator is applied to one or both joint surfaces; adhesive is then applied to one surface to begin curing. Cure speed is determined by the choice of activator; cure times range from less than 30 seconds to greater than 30 minutes. Heat can be used instead of, or in addition to, activators, although its use is not common [1, 15].

Joints produced using anaerobic adhesives can withstand exposure to organic solvents and water, weathering, and temperatures of up to about 200°C (392°F) [1, 14].

Advantages/disadvantages: Advantages include cure-on-demand functionality, low odor levels, single-part room temperature curing and high levels of durability. Disadvantages include limited gap cure, unsuitable for porous surfaces, and poor performance with some thermoplastics.

17.6.2 Epoxies

Epoxy adhesives are polymers that contain epoxy (also termed epoxide) groups in their molecular structure. Most epoxy adhesives contain two end-chain epoxy groups; however, adhesives with more than two epoxy functional groups are also available. Epoxies are usually supplied in the form of liquids or low melting temperature solids, and most contain additives that influence the properties of the material—accelerators, viscosity modifiers, fillers, pigments, and flexibilizers. Flexibilizers reduce sensitivity to localized regions of high stress by reducing the elastic modulus of the bonded assembly. Epoxies are the most commonly used adhesives for composite materials. High-strength bonds can be obtained that have excellent durability and environmental stability [2, 3, 5, 13].

Depending on the epoxy, cure can take place at room or elevated temperatures. Curing of most epoxies occurs through addition reactions of amine or, less commonly, acid anhydride functional groups to the epoxy group of the adhesive, producing a cross-linked product upon completion. Cure by a polymerization reaction initiated by strong organic bases or, less commonly, acids, is possible with some epoxies. Two-part epoxies must be mixed just before curing with stoichiometric amounts of amine or anhydride-containing substances. The rate of cure may be increased by adding accelerators to the reaction mixture or by a temperature increase. Post-curing, exposure of the partially cured material to temperatures that are equal to or exceed the maximum use temperature of the assembly is commonly performed in order to improve structural properties. Post-curing relieves stresses, improves dimensional stability, and results in decreased volatiles in the part [3, 5, 13].

Advantages/disadvantages: Advantages include high levels of adhesion to a wide variety of substrates, high cohesive strength, a wide variety of forms and properties, good toughness, and good environmental resistance. In addition, cure can be accelerated by heat and epoxies offer excellent depth of cure. Disadvantages include the need to mix two-part systems, the requirement of heat or light to cure single-part systems, a limited pot-life/working life (i.e., the interval between the time of mixing and the time at which the increased adhesive viscosity prohibits application of the adhesive to the part surface), and cure rates may be quite slow. In some instances, large volumes of mixed adhesive can give rise to a large exotherm, which will accelerate cure and potentially cause degradation and charring [3].

17.6.2.1 Two-part Room Temperature Cured Epoxies

Two-part, room temperature cured epoxies consist of an epoxy monomer and aliphatic amine curing agent. These are supplied separately (as clear liquids or pastes of varying consistency, from thixotropic liquids to putties), and have indefinite shelf life until mixed. They are mixed before curing at room temperature; pot-life (working life), ranges from a few minutes to a few hours. For some applications, cure time can be a few minutes (e.g., snap-cure epoxies used in some electronic applications). For structural applications, 8–12-hour cure times are usually necessary, and full strength is not achieved for 2–7 days. Room temperature curing materials are usually post-cured; examples of post-curing conditions are 1 hour at 100°C (212°F) or 4–6 hours at 60°C (140°F). Fast-curing epoxies generally have low strength, especially at temperatures greater than 50°C (122°F), and low solvent resistance. These properties are not generally improved by post-curing [13, 14].

Joints produced using room temperature curing epoxies may be brittle, with good shear strength and low peel strength. Temperature resistance extends up to the glass transition temperature, 50°C–105°C (122°F–221°F), which is dependent on the curing agent, curing temperature, and post-curing procedure [13, 14].

17.6.2.2 Two-part Heat-cured Epoxies

Heat-curing epoxies are two-part systems that use less basic primary amines as curing agents; the decreased reactivity requires heating to elevated temperatures. The pot-life is longer than in room temperature cured epoxies, ranging from two hours to several days. The cure temperature depends on the curing agent: cycloaliphatic amine curing agents can be used up to 120°C (248°F), aromatic amines up to 160°C (320°F), and anhydrides up to 250°C (482°F) [13, 14].

Heat-cured materials generally have higher solvent resistance and better mechanical strength than materials cured at room temperature. Cured materials are usually rigid, with high elastic moduli; glass transition temperatures range from 100°C (212°F) to 200°C (392°F). Because of low peel strengths, the untoughened grades of these materials are not recommended for bonding dissimilar materials with very different coefficients of thermal expansion (CTE). Toughening agents or flexibilizers can be added to increase peel strength, they reduce the glass transition temperature, resulting in lower resistance to elevated temperatures but enhanced resistance to low temperatures [13, 14].

The toughness of epoxy joints can be increased by adding a semicompatible rubber to the adhesive system before curing. During curing, cross-linked, epoxy-modified rubber particles become distributed through a glass matrix that is slightly flexibilized. The temperature resistance of rubber-toughened epoxies is decreased to 120–160°C (248–320°F). They are commonly used for structural bonding in the aircraft industry [3, 13, 14].

17.6.2.3 One-part Solid Epoxies

Epoxy polymers with low melting temperatures can be combined with high temperature curing agents or catalysts, such as dicyandiamide, to form one-part solid epoxy adhesives. The adhesive must be prepared as a melt, cooled rapidly, and formed into cast rods, which are then ground to a powder. Solid epoxies that cure at high temperatures (177°C; 351°F) can be stored indefinitely at room temperature; those that cure at ambient temperatures generally require refrigeration. Joints obtained after curing are rigid and strong, with high glass transition temperatures and temperature resistance; however, peel strength is low due to an inability to flexibilize the adhesive system [13, 14].

17.6.2.4 Epoxy Films

In epoxy films, a thin film of epoxy and a high temperature curing agent, such as an aromatic amine, is coated onto a release paper. Toughening or flexibilizing agents may also be present in the film. Woven cloth or short mat, randomly oriented fibers may be added to support the film during handling before curing, and to control adhesive flow and film thickness during bonding. Polyester, polyamide, and glass fibers are commonly used. Woven cloth fibers wick water, resulting in slightly degraded environmental resistance of the adhesive bond. Randomly oriented mat fibers move during bonding and are not as efficient as woven cloth in controlling film thickness. Films can be stored at –18°C (0°F) [13, 14].

For bonding, the film is cut to the required shape and applied to one of the adherends. The release paper is then removed, and the film is pressed against the other adherend. Curing is usually performed by heating for 0.5–1 hour at 121–177°C (250–351°F). Joints are temperature resistant up to 118–178°C (244–352°F), depending on the type of epoxy and the toughening and curing agents used in the film. Joints are normally brittle and exhibit low peel strength. The high structural strength of the joints makes them useful in the aerospace industry and due to the low weight and handling convenience, they are commonly used in laminates [13, 14].

17.6.3 Elastomeric Adhesives

Elastomeric adhesives fall into a number of distinct groups including rubber-based, contact, polyurethane, silicone, polysulfide, and pressure sensitive adhesives [2].

Rubber-based systems (natural and synthetic, high molecular weight rubbers or elastomers) dissolved in either hydrocarbon or chlorinated hydrocarbon solvents, are used as adhesives to produce joints with high peel strength but low shear strength compared to glassy adhesives. They are used when high peel strength is required, such as when bonding a large flexible panel to a rigid composite panel or as contact adhesives that do not require pressure for joint formation to bond decorative films onto exterior panels. Contact adhesives are applied to substrate surfaces for bonding, and solvents are evaporated off by flash-drying before curing. Unsaturated elastomers such as natural rubber and polychloroprene (neoprene) are cured through vulcanization, cross-linking of rubber macromolecules, which commonly occurs through a free radical mechanism initiated by peroxides, or through sulfur cross-linking. Cross-linked rubber adhesives exhibit improved shear strength and creep resistance; however, peel strength is decreased. Joints have limited temperature, solvent, and environmental resistance, especially when the adhesives are not cross-linked.

Other elastomeric adhesives cure through chemical cross-linking, often using moisture in the air, although two-part systems are also available. Lastly, there are pressure sensitive systems, which are mainly based on acrylic, rubber, and silicone chemistry [2, 13, 14].

17.6.3.1 Contact Adhesives

Elastomers including natural, butyl, nitrile, SBR, and polychloroprene rubber are widely used in contact adhesives. These adhesive solutions generally contain additives such as t-butylphenol or coumarone-indene resins to improve tack, and antioxidants to inhibit rubber degradation by atmospheric oxygen. Adhesives are applied to adherends by brush, roller, or spray. Contact cement is used on porous surfaces, such as textiles, and does not require flash drying. Bonding occurs when adherends are brought into contact, with tackiness of the adhesive providing the initial bond strength. Curing does not occur in contact adhesives [2, 13, 14].

Advantages/disadvantages: Advantages include "instant" bonding once the solvent has evaporated, low cost, good durability, high shear strength, and toughness. Disadvantages include limited thermal tolerance, prone to brittleness with age and poor resistance to organic solvents [2].

17.6.3.2 Polyurethanes

Polyurethane elastomers produce a good adhesion to a wide range of substrates, and are available in one- or two-part form, for both room temperature and elevated temperature curing. Curing occurs by a polymerization reaction of an aromatic isocyanate with hydroxy-terminated aliphatic polyethers, polyesters, or amines. The final adhesive displays both rigidity, from the aromatic functional groups, and flexibility, due to the aliphatic portions of the polymer. Different adhesive properties can be obtained by varying the isocyanates and polyethers or polyesters used in the polymerization reaction. Polyurethanes form bonds with good shear and temperature resistance. Polyether-based urethanes are less expensive, but joint strength is lower than polyester-based urethanes. Shear strengths fall with increasing temperature; upper temperature limits are less than 250°C (482°F) and more commonly around 150°C (302°F). Peel strength either falls slowly with increasing temperature or peaks, then decreases. Polyurethanes are moisture-sensitive and will foam in the presence of moisture. Primers are necessary when used with thermosets such as sheet molding compounds. Thermosetting urethane adhesives cannot be reprocessed with thermoplastic substrates for recycling; similar to epoxies, they clog injection screws and must be cut out [2, 13, 14].

Advantages/disadvantages: Advantages include being extremely tough (high impact resistance, good abrasion resistance, high cohesive strength), having high resistance to solvents, a wide range of formulations and properties, and the ability to withstand extreme cryogenic conditions. Disadvantages include a limited depth of cure for single-part systems, mixing requirement for two-part systems, the possible need for a primer, and limited high temperature use.

17.6.3.3 Silicones

Silicone adhesives are derived from polyfunctional siloxanes. They form a tough elastomeric material after curing, and delamination under load from a flexible or semiflexible plastic substrate is lower than that of a more rigid acrylic or epoxy adhesive. They are available in one- or two-part forms. One-part adhesives consist of a silicone polymer and hydrolyzable silane or siloxane catalysts that are activated by atmospheric moisture; they cure at room temperature. Methanol, acetic acid, amines, or oximes formed during curing may cause metal corrosion if vapors cannot escape from the bonded parts. Two-part adhesive systems cure by complex reactions involving acids and polyvalent metal salt catalysts. Cure times range from minutes to hours, depending on the catalyst activity. Curing is generally slower than with other adhesives though new formulations are available that cure through exposure to UV light. Upon exposure to light of correct wavelength and intensity, they will form a tack-free surface and cure to a polymer with up to 80% of the ultimate physical strength in less than a minute. Normally, UV-cure systems are supplemented with a secondary moisture-cure mechanism to address potential noncure or poor cure if areas are shadowed [2, 3, 13, 14].

Silicones do not wet surfaces readily and usually require a primer for good adhesion. Peel strengths of joints are high, but tensile strengths are much lower than with acrylic or epoxy adhesives (6.9 MPa; 1000 psi). They can be used up to temperatures of 220°C (428°F). This is because all silicones have a chemical backbone made up of silicon to oxygen bonds, known as siloxane bonds. It is the high energy of this bond that gives silicones their unique high temperature performance properties [3, 13, 14].

Advantages/disadvantages: Advantages of silicones include availability of single-part systems, solvent-free formulations, room temperature curing, good adhesion to many substrates, high flexibility and a range of different curing formulations. Disadvantages are primarily based around the low levels of cohesive strength, limited depth of cure for moisture cure systems, and potential swelling by nonpolar solvents.

17.6.3.4 Polysulfides

Polysulfides are flexible, chemically resistant elastomers, with a linear polymer structure consisting of aliphatic carbon functional groups separated by one or more sulfur atoms. They are available as either one- or two-part adhesives. One-part adhesives cure slowly and are used primarily as sealants in the construction industry. Two-part adhesives are composed of polysulfide and epoxy resins. They are less brittle than epoxy adhesives and have greater impact resistance and higher elongation. Their tensile strength is lower, however, and they possess a disagreeable odor that is characteristic of polysulfides. Due to their exceptional fuel resistance, they are widely used in the aerospace industry [2, 13, 14, 16].

Polysulfides cure by a cross-linking reaction using inorganic oxidizing agents and polyvalent metals. Joints have reasonable shear and peel strengths and excellent environmental durability [13, 14].

Advantages/disadvantages: Advantages include excellent environmental resistance, high levels of resistance to organic liquids including fuels, good flexibility at low temperature (–62°C; –80°F) and neglible shrinkage during cure. Disadvantages include relatively low cohesive strength, unpleasant odor, creep under loading and very little strength above 121°C (250°F) [2].

17.6.3.5 Pressure Sensitive Adhesives

Pressure-sensitive adhesives (PSAs) are produced and applied in a similar manner to contact adhesives, and instantly provide a level of tackiness. However, in contrast to contact adhesives, the tackiness is permanent and the joining functionality is not time limited. The PSAs are most commonly based on thermoplastic or elastomeric solvent solutions coated on a substrate or on a backing (such as plastic film, paper, or foil) that is used as a carrier. Once the solvent dries/evaporates leaving the adhesive film, the tape is ready for use, or it can be packaged using release paper or on a roll, to be ready at the point of use [2, 14].

Most PSAs are made from formulations based on elastomer (natural, butyl, nitrile, and styrene butadiene rubbers), acrylate or silicone resins. Such adhesives are carefully formulated for good flexibility, tack, and peel strength [14].

Several very high bond strength adhesive tapes have been developed for semistructural applications. Use of a foam carrier acts not only as a gap filler but also helps to distribute the stress within the joint area, thereby improving the overall strength of the joint. Such tape systems offer joint strengths up to ten times those of conventional tape systems, sufficient to support modest loads for long periods of time. The strength of a PSA bond increases over time due to the dynamic and uncross-linked nature of the bonding resin. Initial contact and the application of pressure ensures that the polymer is brought into intimate contact with the substrate surface, however this does not fully engage all of the substrate surface at a micro or sub-micro level. With time the semifluid nature of the adhesive enables it to fully wet out the surface, thereby enhancing bond performance. Full strength may take several days to develop [2].

PSA systems are extremely versatile and will in general provide a good bond to most surfaces with the exception of fluoropolymers and silicones where only very closely matched low surface energy formulations show any success. Double-sided tapes are very much the joining systems of choice within the automotive sector for facia (most often polypropylene) and attachment of secondary components [14].

Advantages/disadvantages: Advantages include instant bonding, ability to bond to most substrates (including polyolefins), environmental durability (acrylate and silicones especially), no mixing, can be cut to fit and there is no mess. Disadvantages include susceptibility to creep, relatively low load-carrying capability, perceived high price, slow to reach full strength and limited bond thickness tolerance.

17.6.4 Hot Melt Adhesives

Thermoplastics are frequently used as hot melt adhesives. They are applied to the adherends at a temperature higher than the melting temperature of the thermoplastic, producing a low viscosity fluid that wets the adherend surface. The parts are then clamped, and the thermoplastic adhesive cools and resolidifies, forming a joint between the two substrates. Hot melt adhesives are in the form of powders, granules, blocks, rods, or film. They can form both rigid and flexible joints and can fill gaps and irregularities between parts. Parts must be assembled quickly, before the molten material solidifies. Many hot melts do not possess good wetting properties [2, 13, 14, 16, 17].

It is recommended that where possible, the surfaces of the adherends are warmed prior to adhesive application thus avoiding potential chilling of the adhesive at the adherend surface and the formation of a poorly wetted surface and a weaker bond.

Semicrystalline thermoplastics, especially polyamides and polyesters, are used for structural applications. Structural hot melt adhesives must be able to wet the adherend surface in a reasonable time at reasonable temperatures without excessive thermal degradation. Polyamides are useful because they melt rapidly to a low-viscosity fluid. Thermal stability of the melt is low, however, and processing temperatures are not much higher than the melting temperature, so that parts must be assembled rapidly [13, 14].

Polyethylenes are useful for general-purpose applications. Polysulfones and EVA copolymers can be used for high-temperature and low-temperature applications, respectively. Polyesters require high temperatures in order to produce a melt with a viscosity that is low enough to adequately wet the adherend surface [14].

Hot melt adhesives are convenient and can be applied rapidly. They provide good resistance to solvents and fuels. High shear strength and moderate peel strength can be obtained; for high peel strength, hot melt adhesives based on thermoplastic rubbers should be used. Since they are not solvent-based, they are nontoxic and are compatible with air quality regulations [13, 14].

Advantages/disadvantages: The main advantages of hot melt systems include low cost, availability of a wide range of formulations, high levels of adhesion to plastics, fast attachment/'cure' and being single-part/solvent free. Disadvantages include poor adhesion to metals, the need for a hot dispensing point (operator safety), rapid cooling, possible thermal degradation, moisture sensitivity, and the possibility of thermal damage to the plastic parts being bonded.

17.6.5 One-part Thermoplastic Emulsions

Some thermoplastics and elastomers are applied as one-part emulsions, polymers dispersed in an aqueous solvent, instead of as hot melts; vinyl acetate polymers are commonly used as a household white adhesive. For most applications, one of the substrates must be permeable to allow water removal from the assembly. Emulsions are used for high-speed production equipment, rapid bonding in the lumber and paper industries, and for bonding wood, paper, fabric, leather, and other porous substrates. The addition of solid fillers to emulsions produces pastes, which are used for tile and wall panel adhesives and sealants. Cleanup is easy with these adhesives, requiring only water [2, 5].

Advantages/disadvantages: Advantages include low cost, use of water as a solvent base, a wide variety of potential fillers and a wide range of viscosities. Disadvantages include slow drying, the need for at least one porous surface, water-based emulsions being susceptible to frost, and poor performance at elevated temperatures.

17.7 Surface Preparation Methods

17.7.1 Overview

Surface preparation of the substrate for adhesive bonding is extremely important in determining joint performance. Without proper surface preparation, even the best adhesive will not produce a durable, high-strength joint. Surface preparation cleans the adherend surface and/or introduces chemical functional groups at the surface to promote wetting and chemical bonding between the adherend and the adhesive. Contaminants include grease, dust, and oil; metal surfaces also become contaminated with oxides generated by corrosion. Surface preparation methods used depend on the class of adherend and the type(s) of surface contaminant(s). Generally, surface treatments can be mechanical, chemical, or electrical. Newer treatments use plasma, UV light or lasers for surface modification. For nonmetal surfaces, cleaning stages consist of an initial solvent cleaning, followed by abrasion or a chemical surface alteration. Solvent cleaning is then repeated. Adhesive bonding should take place as soon as possible after cleaning; a delay of hours, sometimes even minutes can significantly reduce the cleaning effect [1, 14].

Surface contamination can be avoided in composites by the use of a peel ply, a tightly woven, treated nylon or polyester fabric that is laminated onto the surface. This peel ply is peeled off immediately before bonding to expose a clean, roughened surface [13].

17.7.2 Chemical Cleaning Treatments

17.7.2.1 Solvent Cleaning and Degreasing

Solvent cleaning is generally the first surface preparation method applied to the parts. Solvent cleaning removes release agents, such as silicone that may coat the part during molding, and any machine oil transferred to the part. Abrading surfaces coated with oil or grease drives the contaminants further into the parts, and chemical alteration of the surface is ineffective in the presence of contaminants. Solvent cleaning should both precede and follow abrasive treatments. Porous surfaces should be wiped with a lint-free cloth moistened with solvent; the cloth should not be reused. A saturated cloth will not pick up debris particles from the substrate. The length of time required for solvent evaporation will vary according to solvent. A range of solvents are available depending upon the scale of the cleaning operation, environmental control facilities available, and the expected type of contamination [1, 14].

Solvents such as methyl ethyl ketone, toluene, acetone, isopropyl alcohol, trichloroethylene, and perchloroethylene can be used. Substrates can be wiped or sprayed with degreasing solvents, or they can be immersed in an agitated solution for about five minutes. Degreasing alone does not generally clean the substrate well enough to permit chemical surface alteration [1, 14].

17.7.2.2 Detergent Cleaning

Detergents, soaps, and caustic soda are inexpensive and nontoxic. They can be applied by spraying, scrubbing, or immersing the part in an ultrasonically agitated solution. They remove dirt and oil reasonably well, but can react with certain metals to form new contaminants. They should be applied hot to minimize these reactions [1].

17.7.2.3 Alkaline Cleaning

Substrate immersion in an alkaline bath usually follows degreasing. Parts are continuously agitated in a solution maintained at 77–93°C (171–200°F) and an alkaline pH. As dirt, metal chips, and other contaminants are removed, more alkaline solution must be added to maintain the pH, and the bath must be replaced if contaminant levels become too high. After alkaline cleaning, substrates are rinsed in water to remove all traces of the alkaline solution; the solution should not be allowed to dry on the substrates [1, 14].

17.7.3 Mechanical Treatments

Mechanical cleaning involves various methods of abrasion: scouring with powders or metal pads, and rubbing with sandpaper, emery cloth, wire brushes, scrapers, or chipping hammers. Faster "automated" abrasion methods include sandblasting, tumbling, and power sanding. Abrasion methods are more commonly used for metals than for plastics. They remove gross contamination and any low molecular weight material that has migrated to the surface. They produce a roughened surface with increased surface area and may remove softer components from a two-phase material. In composites, abrasion removes the gel coat of the matrix polymer to expose the main structure of the composite. Abrasion results in debris accumulation on the surface from the abrasive, the surface contaminants, and the surface material. These particles must be removed before adhesive application, by wiping with a clean, dry cloth or brush, or by application of filtered compressed air or a vacuum cleaner. In some plastics, especially softer systems such as the polyolefins, abrasion can result in abraded debris still physically attached to the surface, that cannot be removed easily by brushing, vacuuming, or blowing [1, 18].

In adhesive abrasion, the plastic surface is abraded in the presence of a liquid adhesive. Abraded adherends are then immediately mated and the adhesive allowed to cure. Abrasion in the presence of adhesives may produce free radicals, which react directly with the adhesive; abrasion without adhesive produces free radicals which are scavenged by atmospheric oxygen before the adhesive is applied. Adhesive abrasion is commonly performed on fluoropolymers, which are inert, resistant to attack, and difficult to bond [3].

17.7.4 Surface Modification

17.7.4.1 Etching or Oxidation

Ammonium peroxydisulfate, chlorine, ozone, perchlorous and perchloric acid, permanganate, and, most commonly, chromic acid are used to oxidize the surface of plastics. Reactive groups, such as hydroxyl, carbonyl, carboxylic acid, and hydrogen sulfite are introduced, and cavities are formed to provide sites for mechanical interlocking of substrate and adhesive. Chromic acid oxidation or etching is commonly used with polyolefins, ABS, PPO, and acetals. Increases in reaction time and temperature increase the depth of etching with PP; longer etching times increase both etch depth and amount of oxidation in PE substrates [1, 3, 14, 18].

17.7.4.2 Sodium Treatment

Fluorinated plastics are difficult to bond and require highly reactive solutions such as metallic sodium in anhydrous liquid ammonia or sodium naphthanate in tetrahydrofuran. These solutions dissolve the amorphous regions of the surface, increasing mechanical interlocking during bonding by increasing surface roughness. In addition, unsaturated bonds and carbonyl groups are introduced to the surface, increasing chemical reactivity. Sodium treatment darkens the part surface to a depth of about 1 μm, and extended exposure will substantially degrade the part surface. Although the treated surface can remain constant for years, heat and exposure to UV light rapidly degrade it. Sodium etching solutions are very hazardous and degrade rapidly in the presence of oxygen [3, 14, 17, 18].

17.7.4.3 Iodine Treatment

Treatment with iodine is used to alter the surface crystallinity of nylons from the α form, in which amino groups are parallel to the surface, to the β form, in which the amino groups are perpendicular to the surface. Improved adhesion is believed to result from increased chemical activity, and not from mechanical interlocking [3].

17.7.4.4 Surface Grafting

A chemical species can be grafted onto the substrate surface to increase adhesion. When polyethylene is exposed to gamma radiation in the presence of vinyl acetate monomer, the monomer becomes chemically grafted onto the PE surface, increasing the reactivity of polyethylene with an adhesive [3].

17.7.4.5 Thermal Treatment

Exposing the plastic substrate to a blast of hot air (~500°C, 932°F) oxidizes the surface by a free radical mechanism, introducing polar groups (carbonyl, carboxyl, amide, and hydroperoxide) that increase wettability. Cross-linking may occur, and interfacial diffusion during bonding is enhanced by chain scission. Thermal treatment is similar to flame treatment and is commonly used for polyolefins [3].

17.7.4.6 Primers

Primers are sometimes applied to component surfaces before bonding. The solvent is flashed off, leaving the reactive chemical species on the surface. Primers form a chemical bridge between the substrate and adhesive by multifunctional groups that react preferentially with either the adhesive or substrate. Primers are commonly used for acetals, fluoropolymers, polybutylene, polyolefins, polyurethanes, and silicones. Polyolefin surfaces can be bonded immediately; however, silane and isocyanate-based primers, used for silicone and polyurethane adhesives, respectively, must react with atmospheric moisture before adhesive application [3, 14].

17.7.5 Electrical Discharge Treatments

17.7.5.1 Corona Discharge

Corona discharge occurs when an electrode at a high electric potential ionizes the gas surrounding it (Fig. 17.4). The gas discharges the potential. If a plastic film is passed between the high-potential electrode and a grounded electrode, some of the ionized gas particles will undergo chemical reactions with the plastic surface, introducing reactive groups to the surface and increasing surface roughness. Functional groups such as carbonyls, hydroxyls, hydroperoxides, aldehydes, ethers, esters, carboxylic acids, and unsaturated bonds can be produced during this process. Corona discharge is usually performed at atmospheric pressure in air, which oxidizes the surface, although nitrogen is sometimes used as the ionizing gas. It is commonly performed on polyolefins. Polyethylene and polypropylene are treated using an electrical potential of 15 kV at 20 kHz [3, 18].

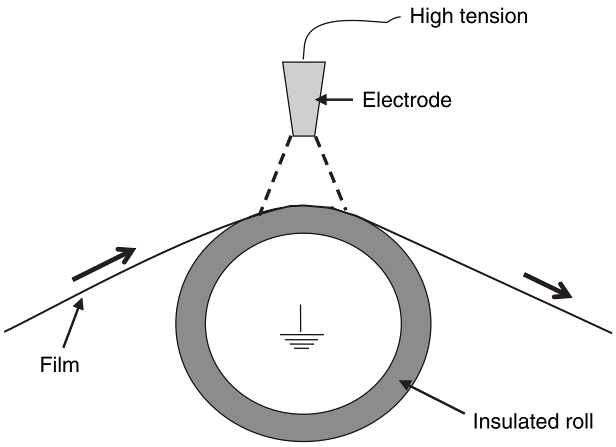


Figure 17.4. Schematic diagram of the corona discharge treatment process (Source: TWI Ltd).

17.7.5.2 Plasma Discharge

In plasma discharge, a gas (oxygen, argon, helium or air) at low pressure (0.1–1.0 torr) is excited by applying radio frequency energy to a pair of electrodes (Fig. 17.5). Electrons are stripped from the gas particles, producing free radicals at high energy levels. Excited gas particles at these high energy levels fall to lower energy levels, resulting in the emission of radiation in the UV and far-UV ranges. The characteristic glow obtained in plasma discharge is similar to that of neon bulbs, fluorescent bulbs, and lightning. When the part to be treated is placed in the low pressure chamber, water, oils, and other organic materials are removed from its surface. Plasma treatment reacts to a depth of 0.01–0.1 μm and reduces the contact angle of the substrate, increasing wettability. Polymers such as PE, PP, PEEK, polyamide-imide (PAI), and liquid crystal polymers (LCPs) can benefit considerably from this process [3, 8, 18].

Substrates should be bonded immediately following plasma treatment, since storage may lead to a reduction

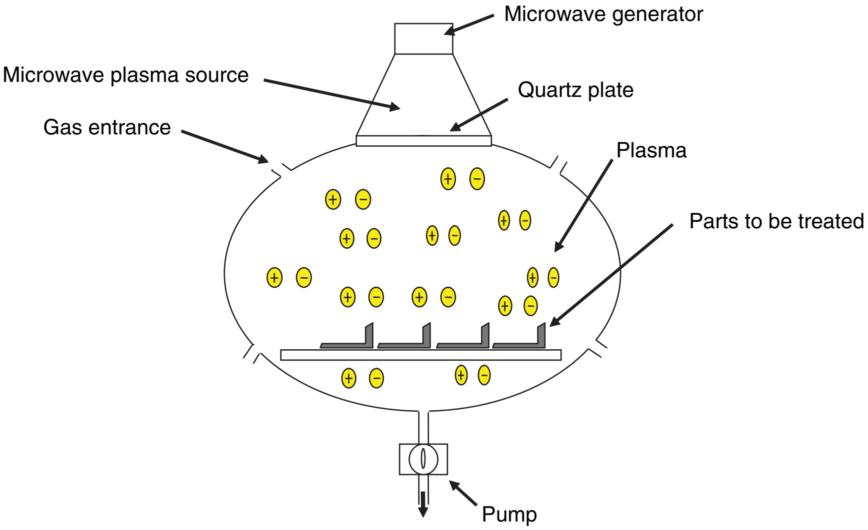


Figure 17.5. Schematic diagram depicting the plasma discharge process (Source: TWI Ltd).

or loss of adhesion to the treated surface. Theories explaining the mechanism of plasma treatment include cross-linking of the substrate surface, which prevents a thin layer of substrate from peeling off; and chain scissions on the surface, which increase interfacial diffusion by lowering surface viscosity and increasing the mobility of molecules at the plastic surface. Plasma treatment is used for many types of plastics. The type of gas used affects joint strengths; ammonia works best with polyphenylene, argon with LCPs, and oxygen with PAI [3, 8, 18].

17.7.6 Other Surface Preparation Techniques

17.7.6.1 Laser Treatment

Laser treatment of PP and PE, using XeCl, ArF, and KrF lasers introduces oxygenated functional groups to the surface and can remove surface contaminants [19].

Surface treatment by CO_2 lasers increases bond strengths in PEI and other engineering plastics, possibly by softening the surface of the thermoplastic adherend [8].

17.7.6.2 Transcrystalline Growth

In transcrystalline growth, substrates are molded against a high energy metallic substrate that causes crystallites to form on the plastic surface. Rod-like or columnar spherulites form inward from the plastic-metal interface, and low molecular weight material is driven into the plastic interior. Oxidation of the plastic surface may also occur, increasing wettability. Molding conditions, such as the cooling rate and mold surface are important in determining the effectiveness of this treatment. This technique can be used for polyolefins, polyamides, and polyurethanes [3].

17.7.6.3 Ultraviolet Radiation

UV radiation at particular wavelengths causes chain scissions, cross-linking, and oxidation of the part surface. Surface changes are dependent on the wavelength of light used; cross-linking of PE will occur at a wavelength of 184 nm but not at 253.7 nm. Proposed mechanisms to describe the enhanced adhesive properties after UV light exposure include increasing the wettability, strengthening the plastic's boundary layer through cross-linking, inducing hydrogen bonding, and especially, promotion of interfacial diffusion, and polar interactions through chain scission [3].

17.7.6.4 Flame Treatment

A brief exposure to flame oxidizes the surface of plastics through a free radical mechanism, introducing hydroxyl, carbonyl, carboxyl, and amide groups to the part surface. Chain scissions and cross-linking also occur, increasing the wettability and interfacial diffusion during bonding. Flame treatment affects the part to a depth of about 4–9 nm and is commonly used on polyolefins, acetals, and polyethylene terephthalate (PET) [3, 18].

17.7.6.5 Removal of Surface Layers

High energy ion beams or radio-frequency plasma discharges can be used to etch the surface and remove surface layers, including surface contamination. A roughened, textured surface is produced for bonding [18].

17.8 Factors Affecting Adhesive Bonding

17.8.1 Stress Cracking

Many plastic parts exhibit stress cracking—external or internal cracks resulting from stresses that are lower than the short-term mechanical strength of the plastic. Thermosets, acetals, PPS, polyolefins, polyamide, rigid PVC, and polybutylene terephthalate (PBT) are normally resistant to stress cracking. Acrylics, PC, PS, SAN, PSO, ABS, and PPO are most prone to stress cracking. Esters, ketones, and aromatic hydrocarbons are the solvents most likely to cause stress cracking [3, 5, 17, 20].

Stress cracking can be induced by strenuous or improper molding conditions, machining operations, or thermoforming at reduced temperatures. The presence of molded-in metal inserts or sharp corners in the part produces greater stress. These conditions can produce small cracks in the plastic; when liquid adhesive is applied, it can penetrate the part, aggravating the damage. The crack may eventually propagate through the entire part, causing failure. Molded-in stresses can be reduced by modifying the molding cycle or annealing parts after molding. Only solvents, adhesives, and primers that are compatible with the plastic should be used. It is therefore important to check the action of a proposed adhesive for any new application or combination of untested materials (see Table 17.3). A minimum of adhesive should be used, and excess adhesive should be cleaned up immediately. Anaerobic threadlocking adhesives should not be used with plastics that are prone to stress cracking. Stresses induced by the threads, in addition to stress from uncured adhesive outside the joint, produce very high stress levels in the part. Surface preparation methods to alleviate stress cracking include abrading the surface with sandpaper, cleaning with isopropyl alcohol, and assembling the parts immediately after application of alcohol [3, 16, 20].

Joining materials with different CTE (linear) can produce stress cracking when the part is subjected to high or low temperatures. Plastics expand at high temperatures and contract at low temperatures by different amounts, depending on their CTE. After bonding, part movement is restricted, and the two materials must expand or contract to the same extent. If the plastics have different CTE, stresses are produced, which lower the strength of the joint. CTE can be decreased by adding fillers or reinforcements or by increasing the amount of cross-linking. If material selections cannot be modified, thicker bond lines and more flexible adhesives can help reduce problems with stress cracking; however, the adhesive film cannot restrain large relative motions of parts. Table 17.4 provides some typical values of CTE for a range of materials [3, 5, 17].

17.8.2 Part Thickness and Colored Dyes in UV-curable Adhesives

When using UV-curable adhesives, increased part thickness or the presence of tints or colored dyes attenuate the light and can decrease bond strength if the cure time is not increased.

17.9 Equipment and Application Methods

Adhesives can be applied to substrates by many different methods. Manual methods make use of simple, low-cost equipment (spatulas, brushes, rollers, squeeze bottles, glue guns) and are usually used in low-speed, low-production applications, but can also be employed in high-speed production lines. Automatic application of adhesives is performed using high-speed, mechanized machines such as roll coaters and flow coaters. Semiautomatic application methods are a compromise between expensive automated equipment and slower inexpensive manual methods. Air-pressured equipment such as spray guns, caulking guns, and high-pressure extrusion guns are used for semiautomatic application. Related equipment necessary for adhesive bonding may include UV curing systems, proper storage facilities, ventilation systems, and safety-related equipment [1, 15].

Spatulas (trowels and putty knives) are useful for difficult-to-spread adhesives and are the only way to spread heavy adhesives. Uniform application is difficult to achieve. Some spatulas have notches along the application edge, which help to control the amount of adhesive applied. Spatula application requires an open adhesive container, which makes ventilation necessary [1].

Brushing is the most commonly used application method. It is a labor-intensive method used to apply adhesive to small areas of large parts, or small or irregularly shaped parts. Uniform adhesive application is difficult to achieve, and some clean-up of drips is

Table 17.3. Stress Cracking Resistance of Various Plastics When in Contact with Cyanoacrylate and Acrylic Based Adhesives

Plastic	Cyanoacrylates	Acrylics
Acrylonitrile-butadiene-styrene	●	●
Acetal	○	○
Acrylic (PMMA)	●	●
Acrylic-styrene-acrylonitrile (ASA)	○	●
Allylic ester (DAP, DAIP)	○	○
Cellulosic	●	●
Epoxy	○	○
Fluoropolymers	○	○
Ionomer	●	●
Liquid crystal polymer	○	○
Phenolic	○	○
Polyamide (nylon)	○	○
Polybutylene terephthalate	○	○
Polycarbonate	●	●
Polyester, thermoset	○	○
Polyetheretherketone	○	○
Polyetherimide	●	○
Polyethersulfone	●	●
Polyethylene	○	○
Polyethylene terephthalate	○	○
Polyimide	○	○
Polymethylpentene (PMP)	○	○
Polyphenylene oxide	●	●
Polyphenylene sulfide	○	○
Polypropylene	○	○
Polystyrene	○	●
Polyurethane	●	●
Polyvinyl chloride	●	●
Styrene-acryonitrile	○	●
Vinyl ester	○	○

○: Normally compatible; ●: should be tested.

required using a solvent cleaner. Flow brushes, in which adhesive flows through the handle to the bristles, are used for high speed production. Application is more uniform, and less waste is produced. Air pressure can be added for semiautomatic application, and ventilation is necessary for solvent adhesives [1, 6, 15].

Dipping is used for completely coating parts and is useful for processing many parts of the same size or parts of different shapes. It is faster than other manual processes and can be automated for greater speed. Masking is required for partial application, and ventilation is necessary for adhesives containing solvent. Dipping is wasteful of adhesive, and many adhesives cannot be applied by this method [6, 15].

Rollers and roll coaters are used to spread heavy or tacky adhesives that cannot be spread by other methods. Manual rollers are made of hard rubber or plastic and are available in many lengths and diameters. Extenders are also available to lengthen the handle. They can be used on many different surfaces. For rollers, adhesive

Table 17.4. Representative Coefficient of Thermal Expansion (CTE) Values for Various Materials

Material	CTE (linear), 20°C	
	μm/m °C	μin./in. °F
Acetal copolymer, 30% glass fiber reinforced	25–43.2	13.9–24
Acetal copolymer, unreinforced	12–162	6.67–90
Acrylic, general purpose, molded	60–130	33.3–72.2
Acrylonitrile butadiene styrene, 40% glass-fiber filled	23	12.8
Acrylonitrile butadiene styrene, molded	65–150	36.1–83.3
Alumina (96%), thick-film, as fired	6.3	3.5
Aluminum	24	13.3
Chromium, annealed	6.2	3.44
Copper, annealed	16.4	9.11
Epoxy adhesive	4.5–86.4	2.5–48
Epoxy, cast, unreinforced	100	55.6
Epoxy/carbon fiber composite	9–14	5–7.78
Ethylene vinyl acetate, molded/extruded	30–160	16.7–88.9
Gold	14.4	8
Graphite, Carbon	0.6–4.3	0.333–2.39
High density polyethylene, extruded	140	77.8
High density polyethylene, injection molded	22–200	12.2–111
Iron	12.2	6.78
Liquid crystal polymer, mineral filled	−10 to 12	−5.5 to 6.67
Low density polyethylene, molded	30–230	16.7–128
Natural rubber, not vulcanized (NR, IR, polyisoprene)	666	370
Natural rubber, vulcanized (NR, IR, Polyisoprene)	225	125
Nickel, annealed	13.1	7.28
Nitrile rubber (NBR, acrylonitrile-butadiene rubber)	702	390
Nylon 11, unreinforced	85–180	47.2–100
Nylon 6, impact grade	20–140	11.1–77.8
Nylon 66, impact grade	20–140	11.1–77.8
Phenolic, unreinforced, molded	77	42.8
Polybutylene terephthalate, unreinforced, molded	50–145	27.8–80.6
Polycarbonate, extruded	70	38.9
Polycarbonate, molded	32–120	17.8–66.7
Polycarbonate/ABS alloy, glass-fiber filled	26–59.4	14.4–33
Polyester (thermoset), rigid	135	75
Polyester (thermoset), molded, synthetic fiber filler	80	44.4
Polyetheretherketone, unreinforced	22–54	12.2–30
Polyethersulfone	31–70	17.2–38.9
Polyphenylene sulfide, molded	15–50	8.33–27.8
Polypropylene, extrusion grade	100	55.6
Polypropylene, molded	25–185	13.9–103

(*Continued*)

Table 17.4. Representative Coefficient of Thermal Expansion (CTE) Values for Various Materials (Continued).

Material	CTE (linear), 20°C	
	µm/m °C	µin./in. °F
Polystyrene	50–125	27.8–69.4
Polytetrafluoroethylene, molded	79–150	43.9–83.3
Polyurethane (thermoset), liquid	42–250	23.3–139
PVC, extruded	45.1–124.5	25.1–69.2
PVC, molded	50	27.8
Silica (96%), glass	0.75	0.417
Silicone, RTV, adhesive/sealant grade	350	194
Steel AISI 1005	12.6	7.28
Styrene/butadiene/styrene	75	41.7
Thermoplastic polyurethane, elastomer, glass-filled	83–250	46.1–139
Thermoset fluoroelastomer	140–260	77.8–144
Tungsten carbide	4	2.22
Zinc	31.2	17.3

must be deposited on the part before spreading; uniformity of spreading depends on the skill of the operator. Roll coaters are automated machines that apply adhesive rapidly and uniformly, with almost no adhesive waste. They are available in a variety of sizes; larger models generally process continuous webs of metal, foil, film, woven fabrics, or nonwoven materials [1, 15].

Spraying is a rapid method used for large application areas. Air spray guns are used to coat plastic, metal, wood, glass, ceramic, leather, paper, and fabric using air pressure to spray a fine mist of atomized adhesive. Airless spray guns use hydraulic pressure to propel the adhesive. Airless spray requires less energy than air spray and is more efficient, and overspray (spray that misses the designated area) is reduced. Use of airless spray also eliminates adhesive contamination from any oil or moisture present in the air. Both air and airless spray guns have heat-source attachments, allowing the use of high viscosity adhesives. Because heated adhesives require less energy to atomize, heavier coatings are possible, and overspray is reduced. However, nozzles can become clogged during operation, requiring shutdowns for cleaning, and spraying is slower than dipping and automated roll coating due to the need to make frequent passes in order to form a sufficiently thick film of adhesive [1, 15].

Spraying can be performed by hand or by using automated equipment. Configurations of many components require hand spraying, in which the control of viscosity is necessary for reproducible application, and a skilled operator is needed to produce a uniform surface coating. Automated equipment consists of a spray conveyor booth, in which adhesive is applied to one side of small components. A large volume of parts can be processed simultaneously as they travel through the booth. Sophisticated mechanical spray systems can be designed specifically for particular coating requirements [15].

Pressure/time applicators include glue guns, needles, and squeeze bottles and can place drops or ribbons of adhesive precisely where needed. Glue guns are accurate and rapid and can be made semiautomatic by attaching an air pressure feed hose. Oil cans and polyethylene squeeze bottles can be used for spot applications; use of a multiple spout tip allows application to several spots simultaneously. Polyethylene squeeze bottles should not be used for adhesives that react chemically with polyethylene and, again, ventilation is necessary for solvents [1, 6, 15].

Silk screening is used to apply low-viscosity adhesives to particular areas of a flat surface. Adhesive is passed through a cloth differing in porosity, preventing adhesive penetration to areas where coating is not desired. This process results in thin films of adhesive and is difficult to use for tacky or fast-drying adhesives [1, 15].

In flow coating, also called veiling or curtain coating, metal, plastic, paper, wood, or leather substrates move along a conveyor and a curtain of adhesive flows down to coat the surfaces. Excess adhesive flows back to a storage reservoir for reuse. Monitoring is necessary since the adhesive viscosity changes as the solvent evaporates, increasing coating thickness. Equipment cleaning is difficult because the adhesive is constantly reexposed to air [1].

Two-component paste adhesives are normally mixed using some type of static mixing head whereby the components are directed into a tube that is internally divided using an insert comprising of alternating helical sections, Fig. 17.6. At each helical section the adhesive flow from both components is split in two directions causing mixing to occur; after 8–15 sections the adhesive is fully mixed with no addition of air, which would normally occur if the adhesive was mixed dynamically, hence the term static-mixing.

For low-to-medium volume production, two-component adhesives are often applied using a gun-type arrangement, which may be totally portable (using a dual cartridge system) or attached to a flexible hose arrangement where larger volumes are required. Such an arrangement also forms the basis for robotic dispensing guns.

Recently, a new approach has been developed, which claims to eliminate the possibility of mixing errors that might occur due to mechanical failure or operator error. The system, termed “Failsafe”, employs a pneumatically controlled measured micro-dose injection system, which enables each micro-dose to be monitored and the equipment will shut down if there is any inconsistency in flow (Fig. 17.7) [21].

In hot melt adhesives, heat instead of solvents liquefies the adhesive. Due to its high speed, hot melt application is commonly used in high-volume packing lines. Equipment used for hot melts include air and airless sprays and wheel, extrusion, or nozzle applicators. The use of sprayers eliminates the need for direct contact with the adherend. Wheel applicators, frequently used for carton sealing, allow adhesive to be dispensed in precise quantities and configurations. Contact extrusion applicators are used in bag making and web conversions [1, 15].

Figure 17.6. Static mixing head system (Source: TWI Ltd).

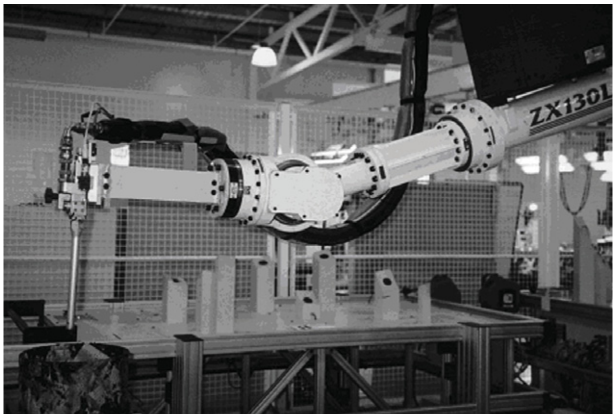


Figure 17.7. Robotic arm with Failsafe head and mixing nozzle (Source: Failsafe Metering International Ltd).

17.10 Joint Design

Joint design in adhesive bonding is an important determinant of the strength, reliability, and durability of the bond. The most effective joint design for a particular application depends on the stresses the part will encounter, and the mechanical properties of the adhesive and adherends.

Joints used in adhesive bonding are shown in Fig. 17.8. The joint must accommodate all loads on the part. For structural joints, the load in one adherend must be transferred through the adhesive layer to the other joint component. Higher strength is generally obtained by larger bond surface areas; for structural load bearing joints with composite adherends, in which the bulk adhesive strength is lower than that of the bulk adherends, the bonded area usually must be larger than the cross-sectional area of the adherends. A lap joint or lap combination joint (joggle lap, double lap, double lap scarf, butt scarf lap) provides maximum surface area for bonding. In T-joints and butt joints, the bond area is limited by the wall thickness of the part; these joints are not recommended for adhesive bonding. For joining curved surfaces, each surface should have the

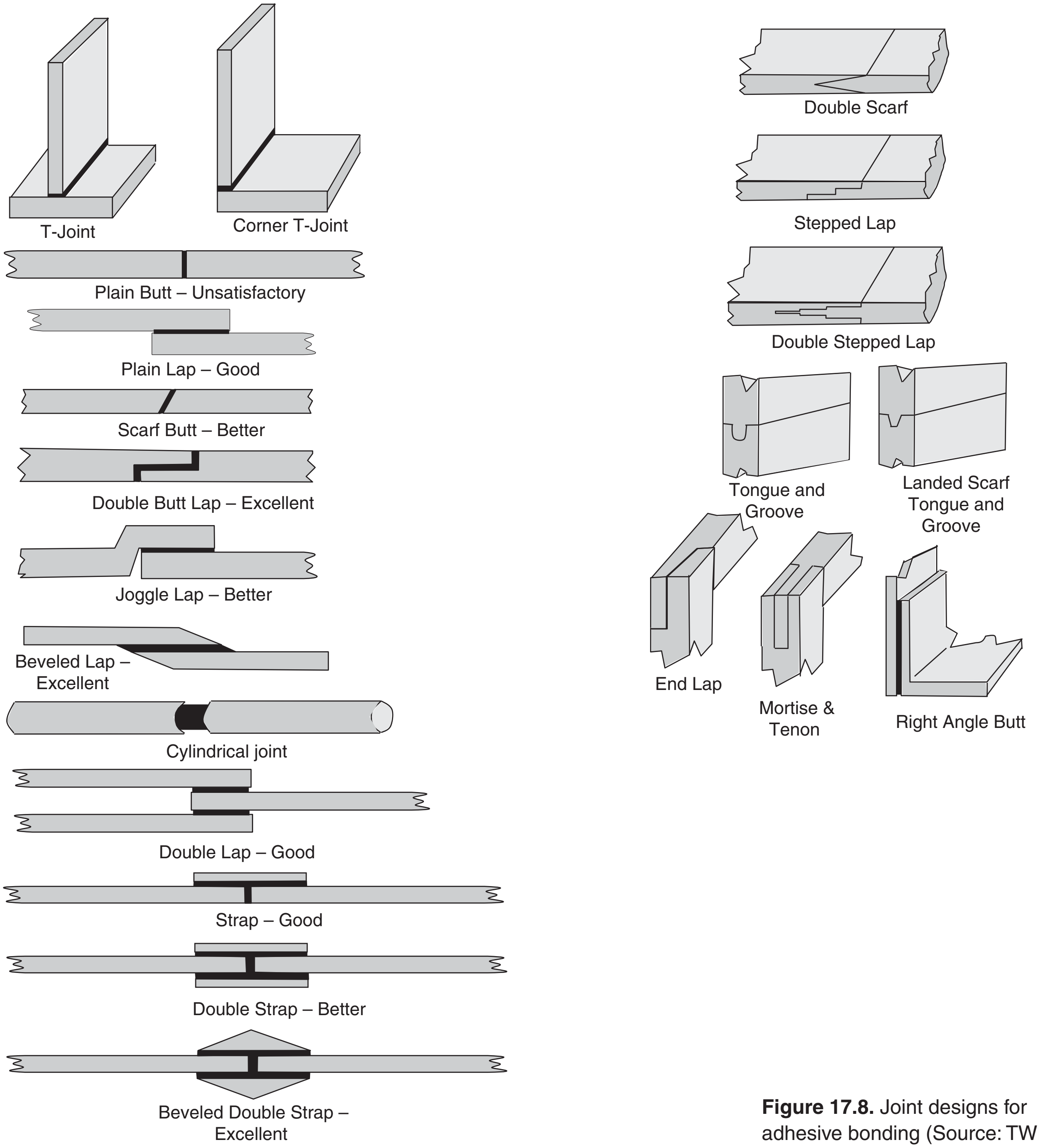


Figure 17.8. Joint designs for adhesive bonding (Source: TWI Ltd).

same radius in order to provide uniform contact over the entire joint area [1–3, 13–15].

Joints are subjected to several types of stresses throughout the lifetime of the part. In tensile stress (Fig. 17.9a), the forces exerted on the part are perpendicular to the plane of the joint; tensile stresses tend to either pull a joint apart, or elongate the part. Compressive stress (Fig. 17.9b) also acts perpendicular to the joint plane but tends to squeeze the parts together. In shear stress (Fig. 17.9c), forces are parallel to the joint plane, and joint surfaces tend to slide over one another. Cleavage stress (Fig. 17.9d) occurs when a joint is opened at one end, and peel stress (Fig. 17.9e) develops when a flexible substrate is peeled or lifted off the other substrate [2, 3, 5].

The stress distribution on the adhesive affects the ability of the joint to accommodate loads. The joint design should strive to distribute the stresses equally

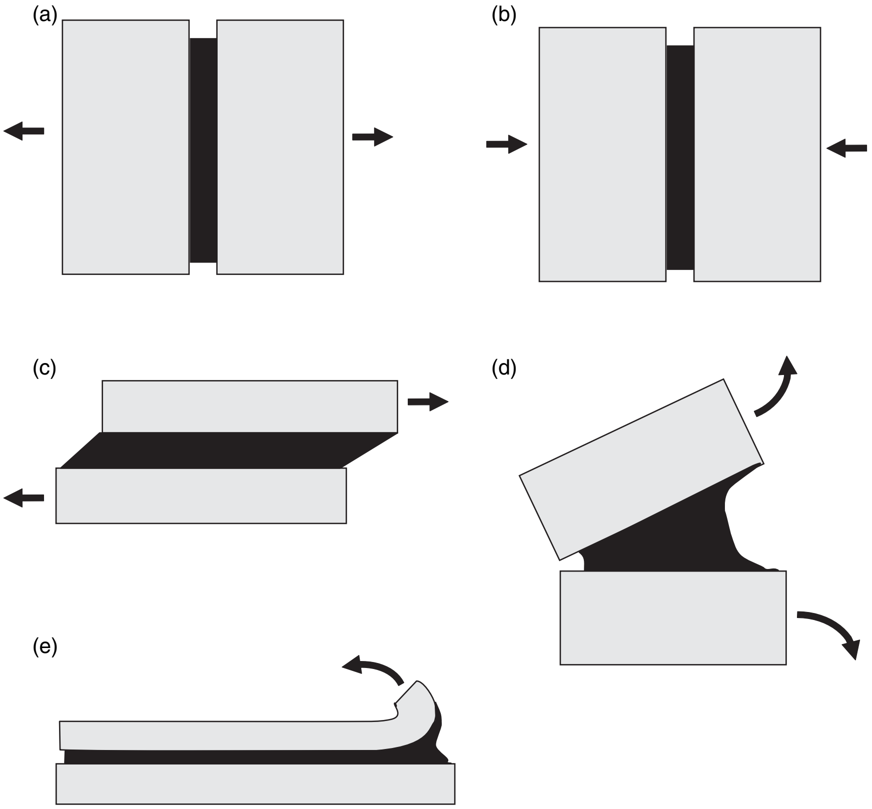


Figure 17.9. Stresses on adhesive joints: (a) tensile stress, (b) compressive stress, (c) shear stress, (d) cleavage stress, and (e) peel stress (Source: TWI Ltd).

over the bond area in order to create a uniform stress on the adhesive. Adhesive bonds subjected to tensile, compressive, or shear stress during loading experience a more uniform stress distribution than bonds exposed to cleavage or peel stress. Tensile and compressive stress is evenly distributed throughout the bond area (Fig. 17.10a). The compressive strength of most adhesive films is greater than the tensile strength; optimal joint design should therefore maximize compression and minimize tensile stresses. The stress distribution of a cleavage or peel stress is concentrated at one end of the joint (Fig. 17.10b). The peel strength of an adhesive may be as low as 1% of its shear strength, although low-modulus, elastic adhesives usually have higher peel strengths. Peel stress can be reduced through symmetrical joints, such as double lap (Fig. 17.8). Joint design should ensure that peel and cleavage stresses are minimized, and shear stress is maximized [2, 3, 13].

In shear stress, the ends of the bond experience a greater amount of stress than the middle of the bond (Fig. 17.11b and d). This stress distribution is partly due to the flexibility of plastic materials, which tend to bend when a load is applied, increasing stress concentrations at the joint ends. Stress ratios (highest stress/average stress) of plastics with relatively low elastic moduli (2068 MPa; 300 kpsi) are around 15.0, which is much greater than stress ratios for steel (around 1.7). Stress concentrations can lead to joint failure at relatively low loads; however, these can be reduced by a joint design that takes into account the elastic modulus of the adhesive, the joint overlap length, and the bond line thickness [1–3].

The elastic modulus of the adhesive influences the stress distribution of the joint. The shear stress distribution of a more brittle, higher modulus adhesive with a stress–strain curve as shown in Fig. 17.11a shows a large increase in stress at the ends of the joint (Fig.17.11b). A more elastic adhesive with a greater elongation and stress-strain behavior, as shown in Fig. 17.11c, exhibits a more uniform stress distribution (Fig. 17.11d). The flexibility of the more elastic adhesive allows the joint to more easily accommodate motion of the adherends during loading; stress is then distributed over a larger area, and the stress ratio is reduced. Using a lower modulus (1.4 MPa; 200 psi) adhesive in place of a higher modulus (2068 MPa; 300 kpsi) adhesive can reduce the stress ratio from 22.4 to 1.2. Although a lower modulus adhesive may produce a stronger joint for some applications, it may not be able to accommodate structural loads without excessive deformation. Due to the greater area under the stress distribution curve, the more elastic adhesive experiences a higher

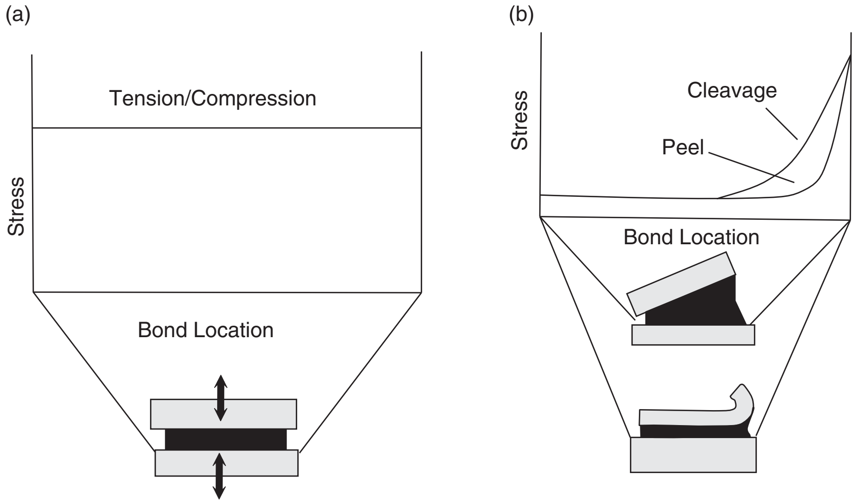


Figure 17.10. Distribution of stress along the joint: (a) tensile and compressive, and (b) peel and cleavage (Source: TWI Ltd).

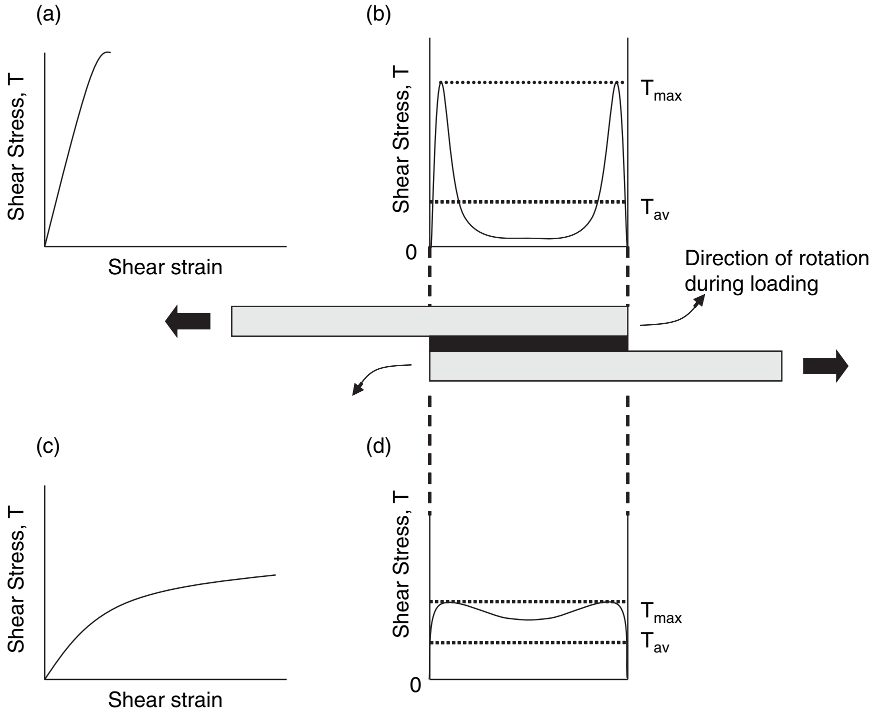


Figure 17.11. Shear stress distribution in brittle and elastic materials: (a) stress versus strain curve for brittle adhesive, (b) stress distribution in brittle adhesive joint, (c) stress versus strain curve for elastic adhesive, and (d) stress distribution in elastic adhesive joint (Source: TWI Ltd).

average stress than a brittle adhesive of the same strength. Brittle adhesives, however, are more sensitive to crack propagation and generally have lower fatigue life than more elastic adhesives [1–3].

Although bonds with larger areas generally have higher strength, bond width is a more important design parameter than bond length or overlap. Bond strength increases initially with overlap length up to a point, then levels off to a constant value. Due to the shear stress concentration at the ends of the joint, shear strength is directly proportional to bond width. A 2 cm (0.8 inch) wide joint is twice as strong as a 1 cm (0.4 inch) wide joint, but a 2 cm (0.8 inch) long joint is not twice as strong as a 1 cm (0.4 inch) joint. A short, wide joint area (Fig. 17.12b) is stronger than a long, narrow joint area (Fig. 17.12a). Bending and differential shear stress concentrations are reduced with shorter joint overlaps and a decrease in overlap length from 2.5 cm (1.0 inches) to 0.32 cm (0.13 inches) can result in a reduction of the stress ratio from 22.5 to 3.78 [1–3].

A thicker bond line can reduce shear stress concentration by spreading the strain over a larger dimension, resulting in lesser strain on the adhesive. An increase in bond line gap from 0.025 mm (0.001 inches) to

1.0 mm (0.04 inches) can decrease the stress ratio from 18.4 to 3.06 [1–3].

The most common method for reducing stress concentration in lap joints is by tapering the adherends in a tapered lap joint (Fig. 17.13a). Stress at the joint ends is reduced, allowing for a more uniform stress distribution. Modeling studies have shown that both adhesive peel and shear stresses decrease with a decrease in taper angle, with the optimum angle being the smallest angle that can be economically machined and assembled. A step lap joint (Fig. 17.13b) can be used to avoid a large change in stress concentration from the ends of the joint to the center when long overlap lengths are necessary [1, 2, 8].

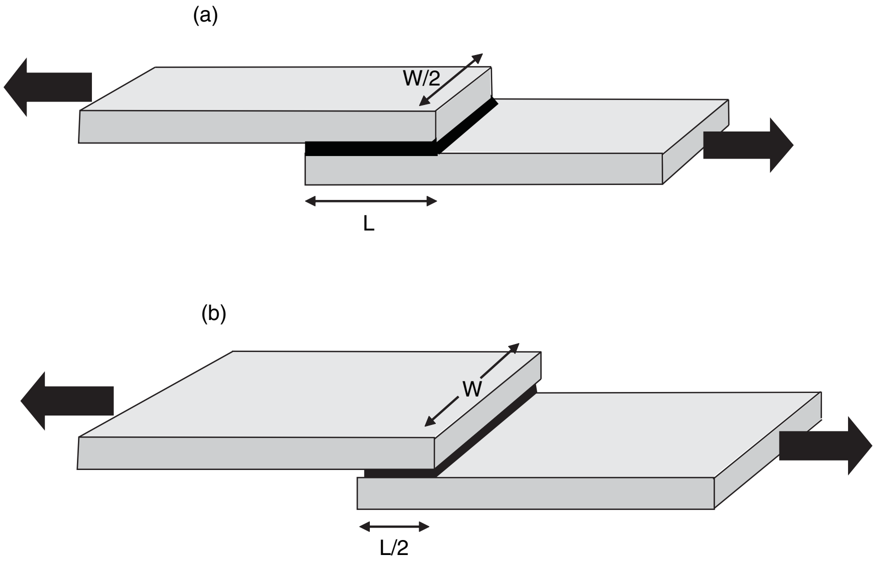
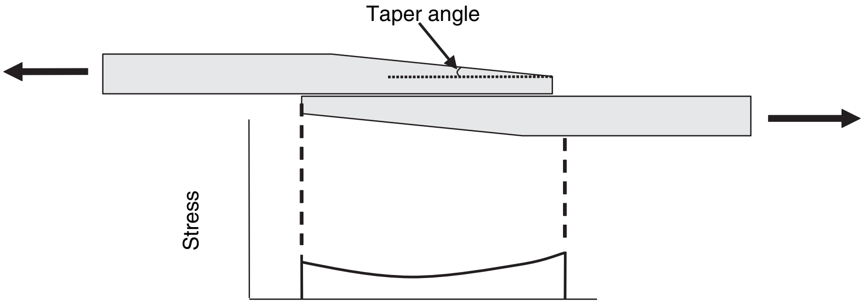
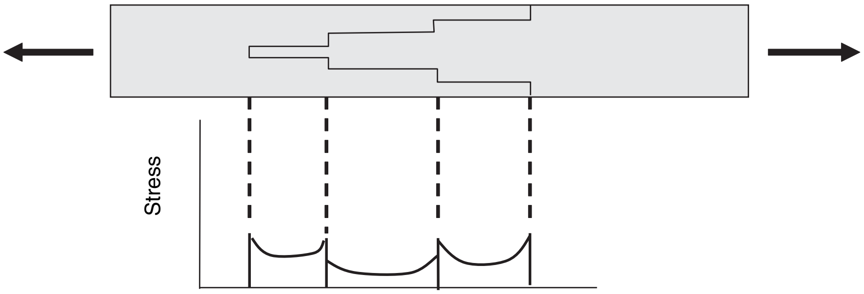


Figure 17.12. Dependence of shear strength on bond geometry. (a) A long, narrow bond area produces a lower strength joint than (b) a short, wide bond area (Source: TWI Ltd).



(a) Tapered Lap Joint



(b) Step Lap Joint

Figure 17.13. Joints used to reduce stress concentrations in adhesive bonding: (a) tapered lap joint, and (b) step lap joint (Source: TWI Ltd).

17.11 Hybrid Joining

Sometimes, it is appropriate to combine adhesive bonding with an additional joining process, thereby creating a hybrid joint. In the case of plastics, the most common additional process is mechanical fastening. The fasteners can take the form of threaded components or rivets, and their function can be either primary (providing the main load carrying function with the adhesive acting as backup or as a sealant) or secondary (acting as an assembly aid or as a load carrying backup). In almost all cases, fasteners require holes to be made in both components to be joined, and in many cases such holes can be the source of parent material failure due to the local stresses that such features create. It is the role of the surrounding adhesive to absorb such stresses during the life of the structure.

An example of a where the adhesive has a secondary role is in the assembly of aircraft wings comprising of carbon composite material where design codes require the primary joining method to be by metallic fastener, despite the use of a structural adhesive for this application. However, the presence of an adhesive to fully seal the wings (and create fuel storage areas) is still required. In contrast, boats and yachts produced from GRP will utilize the adhesive as the primary structural joining method, but will still require a limited number of fastener positions to enable alignment during assembly, and to create pressure along the joint during cure.

Fasteners can fulfill a number of tasks when applied correctly within a hybrid joint. One approach has been to maximize functionality by making the fastener part of the system to simplify assembly, control fit-up tolerances and adhesive bond-line thickness, provide a means to introduce adhesives directly into the joint, and to give the joint secondary backup strength (Fig. 17.14). The AdhFAST fastener contains an internal spacer which holds the joint apart a fixed distance. Channels positioned either centrally or down the sides of the fastener then allow the adhesive to be injected directly into the joint cavity. Injection opens up the possibility of automated assembly and a minimization of human error. A range of designs is possible, depending on the application.

17.12 Adhesive Bonding Tips

- Using adhesives with mechanical fasteners aids in assembling the adhesive joint and reduces peel loads at the edges of lap joints, in addition to providing extra strength.
- Acrylic adhesives that use either adsorbed moisture on one adherend or catalyst application to one adherend are generally not suitable for joining poor-fitting surfaces. These adhesives will fill gaps reliably only up to 0.25 mm (0.01 inches). Fluid adhesives may flow excessively in joints with large gaps if surface forces do not prevent runoff. Thixotropic, filled adhesives should be used instead.
- The most common source of voids in heat-cured adhesives is evolution of gases from volatile materials in the adhesive; water vapor is the most common gas given off. If adhesive is cured above the boiling point of water, moisture contamination should be avoided, and the adhesive should not gel below the boiling point of water under the curing conditions. Another source of voids is air trapped during mixing of two-part adhesives and during joint assembly. If this air is not expelled when the parts are clamped, or if the adhesive is too fluid, it can become entrapped within the adhesive in the bond line.
- Thermal stresses may develop if dissimilar adherends are bonded using heat-cured adhesives, resulting in joint failure or part distortion after cooling. Thermal stresses can be minimized by reducing the temperature at which the adhesive gels; post-curing will be required in order to increase the glass transition temperature of the

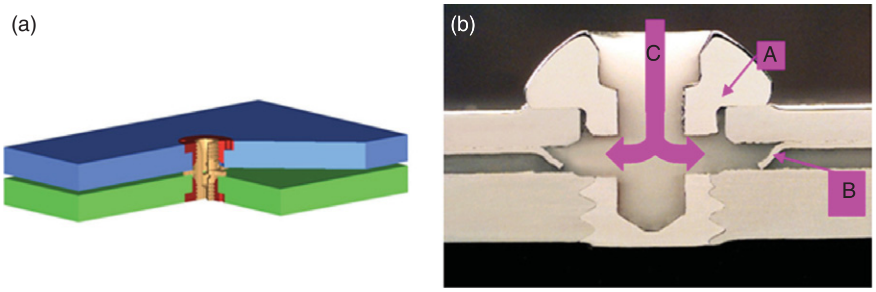


Figure 17.14. AdhFAST system: (a) schematic of an AdhFAST structure, and (b) cross-section detail of AdhFAST™ fastener (A: main fastener body; B: spacing element, and C: adhesive path) (Source: TWI Ltd).

adhesive. Careful joint design can prevent the formation of thermal stresses.

- Any adhesive that adheres well to the surface of the adherend should produce an impervious, air- and water-tight seal with careful joint design. Urethanes or very viscous, ductile acrylics seal imperfect joints well, without being too difficult to apply.
- Mechanical fasteners, such as screws or inserts, work better than adhesives for very small joint areas that must carry a high load, especially if there is no allowance for cure time in the production cycle. A cyanoacrylate adhesive may be suitable if it does not embrittle the plastic or result in stress cracking.
- Adhesives used for bonding thermoplastics to metals depend on the application requirements. A flexible adhesive should be used if the assembled part will be exposed to large temperature changes, to accommodate the significant differences in CTE. Urethane adhesives are ductile and bond well to thermoplastics and metals. Acrylics can also be used if the environmental temperature variation of the part is insignificant.
- When received, adhesives should be tested for compliance with specifications. Physical and chemical tests for moisture content, resin content, base resin, secondary resins, curing agent, and accelerator should be performed.
- Selection of a structural adhesive should include durability tests for the combined effects of heat, humidity and/or fluids, and stress.
- Adhesives should be stored at as low a temperature as possible within the recommended temperature range.
- Cold adhesive should be warmed to room temperature in a sealed container. If possible, paste mixes should be degassed.
- Humidity in the lay-up area should be below 40%, since water is absorbed by the adhesive and released during heat curing as steam, interfering with the chemical reactions and producing porous joints.
- Heat curing is usually preferred for composite materials; joints have higher strength, and heat and humidity resistance.
- The temperature of a second cure (such as for repairs) should be at least 28°C (50°F) lower than the first cure temperature. If this is not possible, the part must be maintained in proper alignment during the cure cycle.
- Exposed composite joint edges should be protected with an elastomeric sealant or paint. Honeycomb assemblies should be hermetically sealed.
- Traveler coupons, composed of the same material and having the same joint design as the adherends, should be made for testing. They should be cut from the same basic part as the adherends. Coupon surfaces should be prepared identically to the adherends, and surface preparation and bonding of both coupons and adherends should be performed together with the same adhesive.
- Adhesives used in sandwich structures must bond an open cellular honeycomb core to a stiff, continuous facing. The flow of adhesive must be carefully controlled to prevent it from flowing down the cell wall, producing a low-strength top-skin bond and an overweight, bottom-skin attachment. If the two surfaces to be bonded do not fit precisely, the adhesive can be squeezed out when pressure is applied to a local area of the part during curing, resulting in a region of low bond strength. Squeeze-out of all the adhesive can be prevented by casting a scrim cloth, an open-weave cloth or fibrous web, within a thicker adhesive film.

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18 Mechanical Fastening

18.1 Introduction

Mechanical fastening still remains the most common method of joining many materials within industry, due to its simplicity. Although originally used for metal joining, it is also well-established for joining plastics to themselves and to other materials.

There are two main categories of industrial fasteners, referred to as permanent and nonpermanent. Screws are examples of nonpermanent fasteners, since they can be removed, replaced, and reused. These parts, however, increase the product cost due to the increased assembly time and can be more difficult to handle and align. Permanent fasteners, such as snap-fits, which are integrated into the parts through direct molding, are more robust and do not have the potential for working loose. As a result, the use of permanent fasteners is increasing [1, 2].

Different types of mechanical fastening techniques are described in the following sections.

18.2 Machine Screws, Nuts, Bolts, and Washers

Machine screws, nuts, bolts, and washers are all examples of nonpermanent fasteners and materials joined in this way can be disassembled and reassembled a number of times until the material being joined fails. Failure is normally as a result of cracking or crazing due to tensile stresses that can be induced under high pressure. Compressive stress is much more desirable due to the lower susceptibility to localized stress cracking [3].

Machine screws and bolts used in joining plastic parts should have a flat side under the screw head (Fig. 18.1). Screws with a conical underside produce potentially high tensile stresses due to wedging of the screw head into the plastic part. Screws with flat undersides, such as the pan-head screw, do not undergo this wedging action, and the stress produced is more compressive. Flat washers distribute the assembly force and should be used under the fastener head [4, 5].

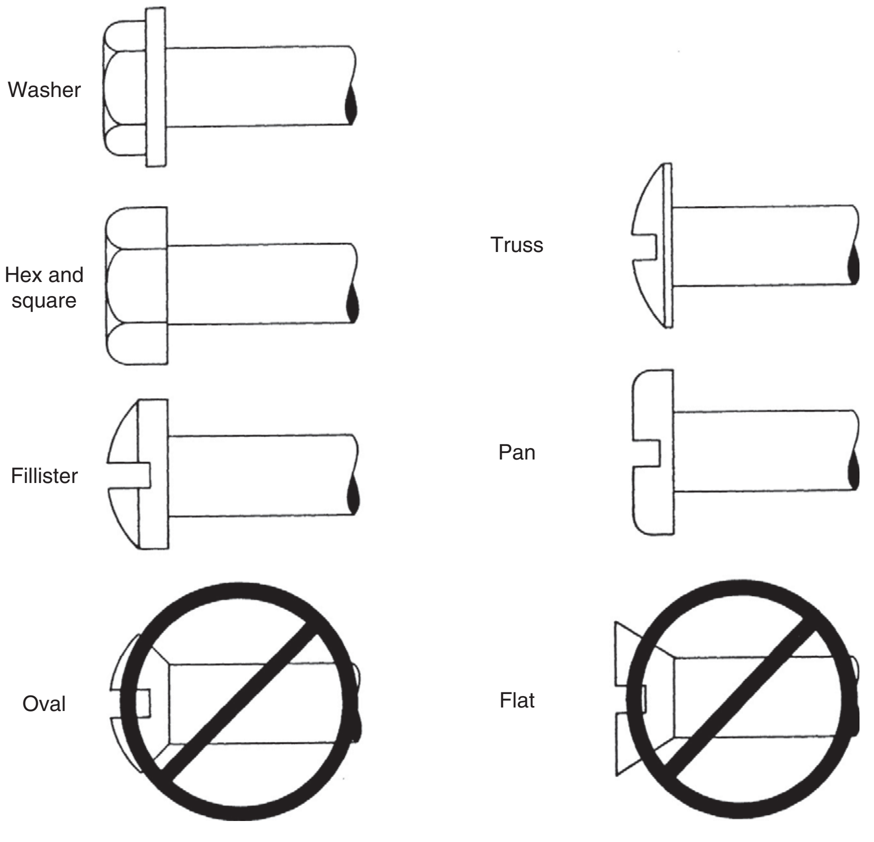


Figure 18.1. Common types of screws and bolts. A flat underside is preferred (Source: Bayer Corp.).

The parts being joined should provide enough diametral clearance for the body of the screw (Table 18.1) [5, 6].

Screws or threaded bolts with nuts pass through the plastic part and are secured by an external nut or clip on the other side. For compressive, rather than tensile loading, any space between surfaces of parts being assembled should be eliminated, using spacers if necessary (Fig. 18.2a). Some part designs may require a loose-fit gap between bosses to prevent high bending stresses or distortion, as the parts go into compression (Fig. 18.2b) [7–9].

Excessive compressive forces can result from use of high assembly torques. To reduce compressive stress in the assembled parts, either a lower torque should be used, or the area under compression must be increased by using a larger screw head or washers under the screw and nut. A shoulder screw or stepped washer can also reduce the compressive stress when joining a plastic part to a metal part [7, 9].

Table 18.1. Recommended Hole Diameters for Machine Screws

Screw Size	Hole Diameter	
	Inches	cm
#2	0.096	0.244
#4	0.122	0.310
#6	0.148	0.376
#8	0.174	0.442
#10	0.200	0.508
#12	0.226	0.574
1/4	0.260	0.660
5/16	0.323	0.820
3/8	0.385	0.979

18.3 Self-tapping Screws

18.3.1 Description

Self-tapping screws are installed into drilled or molded pilot holes. They either physically cut through the material to form a thread, or form a mating thread as a result of material deformation. Installation of this type of fastener is rapid and no nuts are required to secure the fitting. This type of fitting is a popular choice for joining materials due to the excellent holding force. However, incorrect assembly may lead to thread damage and lower pull-out strength than some of the other fastening methods [1, 8, 10].

18.3.2 Advantages and Disadvantages

Self-tapping screws are a reliable and inexpensive method of mechanical fastening. They do not require molded-in threads or threaded inserts, reducing molding and assembly costs. Dissimilar materials can be joined, and disassembly and reassembly of the joint is possible, often up to ten disassembly/reassembly cycles. Connections have good impact resistance and can be made in localized regions of the part. Full-strength joints can be obtained immediately, without the cure time associated with adhesive bonding, and no special application tools are required [11, 12].

However, stress concentrations at attachment points are likely, along with a difficulty in obtaining impervious seals. Aesthetic considerations may be affected by fastener location in accessible areas of the part, and the need for a diversity of screw types and sizes may increase inventory costs [11].

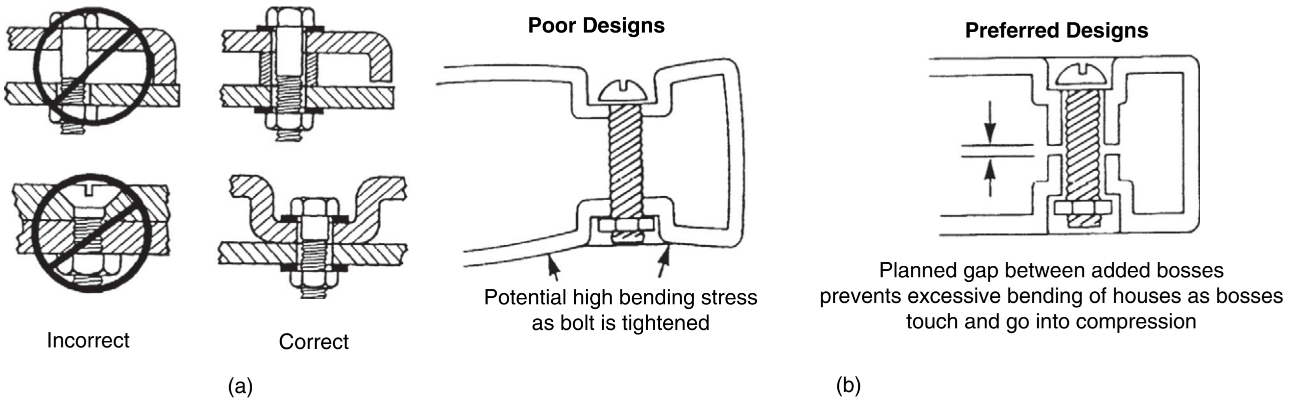


Figure 18.2. Boss designs to eliminate bending stress: (a) use of a spacer, and (b) use of a planned gap between bosses.

18.3.3 Classification

The two basic classes of self-tapping screws for plastics are thread-forming and thread-cutting, the properties of which are described in greater detail in the following sections.

18.3.3.1 Thread-forming Screws

Thread-forming screws form threads by displacing and deforming the plastic material, which then flows around the screw threads. As no material is removed from the product, a fit with zero clearance is created; this can produce large internal stresses. These types of screws are therefore only normally suitable for soft plastics, with a flexural modulus below 1380 MPa (200,000 psi). Thread-forming screws are renowned for their low cost and excellent resistance to vibration, even though they can be assembled and disassembled.

18.3.3.2 Thread-cutting Screws

Thread-cutting screws have a sharp cutting edge removing material as it is inserted. It is therefore important for the hole depth to be slightly longer than the screw, so that the removed material is deposited from the device and does not become trapped internally. This type of screw reduces the creation of internal stresses and is therefore more suitable for higher stiffness materials, that is with a flexural modulus between 1380 MPa (200,000 psi) and 6900 MPa (1,000,000 psi).

For fiber-reinforced plastics, thread-cutting screws give excellent performance due to high thread engagement, high clamp loads, and minimal residual stresses, which can all generate failure following insertion of the fastener. For brittle plastics, that is, with a flexural modulus above 6900 MPa (1,000,000 psi), during insertion of the thread-cutting screw, granulation can take place leading to the entrapment of debris between the screw threads, leading to pull-out at lower predicted force values. To overcome this problem, screws with finer threads are recommended for fastening these types of material. If repeated reassembly of brittle plastics is required, then it is recommended that a metal insert is used, as the hole would otherwise become too big to reuse the same screw type.

Only a minimal number of reassemblies can be carried out with thread-cutting screws as the thread can become stripped. If removal and reassemblies are necessary, then a Type-T screw should be used initially and then replaced with a standard screw. This type of self-tapping screw provides acceptable performance in solid wall parts, but is not recommended for structural foam [1, 5, 7, 11].

18.3.4 Types of Self-tapping Screw

The types of self-tapping screws and their properties and application, are given in Table 18.2.

The selection depends on the requirements of the application and the type of plastic used in the part. For example, if the application requires vibration resistance, then a Plastite thread would be a good choice. However, if the requirement is to reduce hoop stress in thin boss walls a Type-BT thread-cutting screw may be appropriate. Screw selection for a particular type of plastic largely depends on the modulus of elasticity of the material [4, 11].

18.3.5 Boss Design

Bosses are generally used as an anchor for self-tapping screws. Their design is influential on the performance of the screw and the appearance of the final part. The geometry of the boss is dependent on the screw type being used, since the wall thickness must be sufficient to absorb the strain. The design of the boss is also dependent on a number of factors, including location on the part, hole dimensions, draft angles, and gusset supports [11, 13].

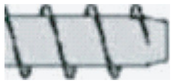
18.3.5.1 Location

The location of the boss within the part to be joined is of great importance. Bosses should not be included in part walls, as this increases wall thickness and leads to flow restrictions, resulting in surface imperfections. The bosses must be free-standing and attached to the nominal wall by ribs (Fig. 18.3) [3, 11].

18.3.5.2 Gusset Supports

These are modified ribs that are usually triangular in shape (Fig. 18.4). They increase the strength of the boss with respect to lateral and longitudinal forces. Gussets that are less than two-thirds the height of the boss allow the boss to expand slightly when screws are inserted, in order to relieve stress. Gusset supports should be used for screws of 6 mm (0.24 inches) and above [11].

Table 18.2. Types of Self-tapping Screws

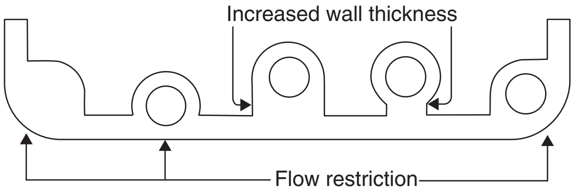
Name	Screw Type	Properties	Application	Schematic
AB	Thread forming	Do not contain cutting slots Do not produce chips 60° thread angle	Materials with a modulus less than 2760 MPa (400,300 psi)	
B	Thread forming	Large root diameter, finer thread pitch	Designed for wood and metal, but also used for thermoplastics	
BF	Thread cutting	Wide thread spacing can suffer clogging of the cutting slots when working with softer materials	Materials with a modulus greater than 2760 MPa (400,300 psi)	
BP	Thread forming	Same dimensions as B, but has a cone point for use where holes are slightly misaligned	Materials with a modulus less than 2760 MPa (400,300 psi)	
BT	Thread cutting	Formerly known as Type 25 Most common Wide thread spacing	Materials with a modulus greater than 2760 MPa (400,300 psi)	
D	Thread cutting	Formerly known as Type 1 Good for field replacement	General use	
F	Thread cutting	Blunt tapered point Multi-cutting edges Chip cavities	Both metals and plastics	
T	Thread cutting	Formerly known as Type 23 Fine thread spacing to reduce granulation	High modulus (greater than 7000 MPa; 1,015,000 psi) glass reinforced materials	
Hi-Lo™	Thread forming/ thread cutting	Double lead screw – high thread 30° – low thread 60°	Designed for thermoplastics Excellent pull-out due to the increased contact with plastic between the high threads	
Trilobe™	Thread forming	Also called Plastite Triangular spaced threads – single lead – double lead Thread angles 45–48°	Increased resistance to loosening, ideal for vibration applications	

18.3.5.3 Boss Dimensions

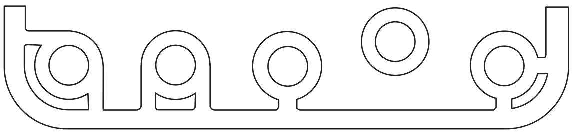
The boss hole dimension is an important factor as the depth of the boss pilot hole should be equal to the height of the boss wall (Fig. 18.5). A hole that is too deep can result in restricting flow of material on the side opposite the boss wall, whilst a hole that is too shallow may cause the material below the hole to cool unevenly, creating sink marks. To prevent excessive loading of the screw threads, the depth of the hole should be slightly greater than the length of the screw used [11, 14].

The hole diameter before screw insertion should generally be equal to the pitch diameter of the screw (Fig. 18.5), in order to achieve a high ratio of stripping to driving torque. A slightly smaller hole diameter (80% of the pitch diameter) can be used to achieve higher stripping torques, especially with thread-forming screws [5, 10, 13, 15].

The outside diameter of the boss should normally be between two and three times the screw diameter; if the diameter is less than this, then cracking is likely to occur. On the other hand, if the diameter is greater than



(a) Incorrect:
Bosses are included as part of side wall



(b) Correct:
Bosses are separate from side walls or attached by ribs

Figure 18.3. Boss location.

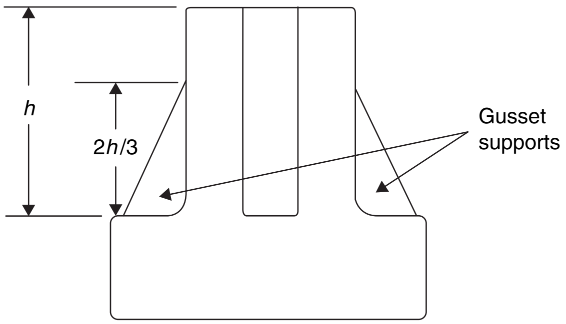
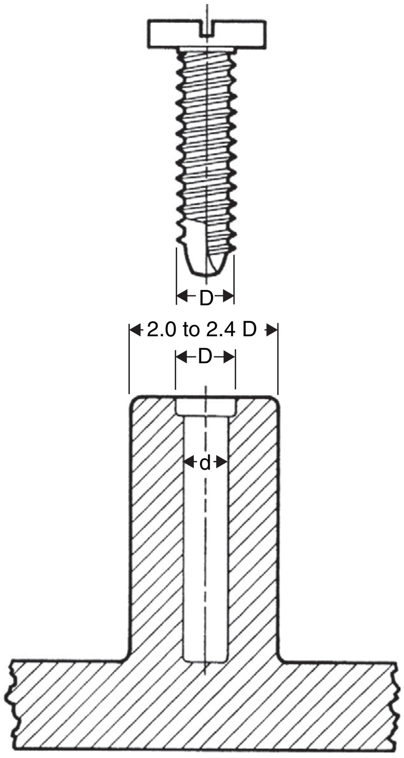


Figure 18.4. Design of gusset supports.

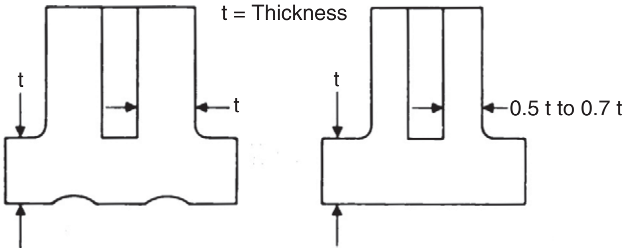
this, then no increase in the stripping torque is achieved. In order to avoid sink marks, the thickness of the boss wall should not be greater than 70% of the thickness of the nominal base of the boss (Fig. 18.6). When cosmetic considerations are important in solid plastic parts, boss wall thickness should not be greater than 50% of the nominal wall. For structural-foam parts with thicker walls, the boss wall thickness can extend up to 80% of the nominal wall thickness [11].

The final factor that can affect the design of the boss is the screw length. Stripping torque increases rapidly with screw length due to a higher engagement, but does tend to level off when the engagement length reaches 2.5 times the pitch diameter of the screw. Significant increases in pull-out strength can be achieved with only slight increases in the engagement length; however an increase in the screw diameter has little effect [10, 13, 14].



Screw Size	Diameter	
	d ± 0.002 in (± 0.0005 mm)	D ± 0.002 in (± 0.0005 mm)
#6	0.123 in (3.1 mm)	0.140 in (3.6 mm)
#8	0.145 in (3.7 mm)	0.166 in (4.2 mm)
#10	0.167 in (4.2 mm)	0.189 in (4.8 mm)
#12	0.191 in (4.9 mm)	0.219 in (5.6 mm)
¼"	0.220 in (5.6 mm)	0.250 in (6.4 mm)

Figure 18.5. Design of boss pilot hole.



(a) Incorrect solid boss design: thickness of boss wall is greater than 70% of nominal wall thickness

(b) Correct solid boss design: thickness of boss wall is 50% to 70% of nominal wall thickness

Figure 18.6. Boss wall thickness.

18.3.5.4 Draft Angles

Draft angles are features cut into the surfaces of the boss. The angles should be kept to a minimum

(0–0.5°) on the inside of the boss, as this ensures consistent screw engagement. If draft angles are too large, the screw will be loose-fitting at the top of the hole and too tight a fit at the bottom, which introduces high stresses. As the boss design incorporates a thicker wall in the base of the boss, the top is susceptible to hoop stresses, which can lead to cracking.

For screw selection in bosses with draft angles, the average hole diameter is used by screw manufacturers to determine the screw size [11].

18.3.6 Torque

The torque used for screw insertion influences the quality of the connection. Self-tapping screw connections are frequently damaged during assembly due to the application of excessive torque. The amount of torque used for a screw depends on the total number of threads and the cross-sectional area of the boss. Self-tapping screws usually have sufficient threads, but very small thread engagement lengths may result in excessive application of torque [6].

Figure 18.7 shows the variation of torque as the screw is turned. Initially, the torque must be applied to cut or form the thread in the plastic (forming torque) and to overcome the sliding friction of the threads (friction torque). These initial torques are combined into the drive torque. Drive torque increases with screw rotation as the thread engagement length increases up to point A on the curve. At point A, the head of the screw seats. As greater torque is applied, compressive loading of the plastic threads begins to occur, until at point B, the stress in the threads reaches the yield point of the plastic, and the threads then begin to strip. Stripping torque, the torque required to strip the plastic boss threads, is the torque at point B. Threads continue to strip until at point C, the screw connection completely fails. Screws are generally tightened to a point between points A and B (tightening torque) [10–12].

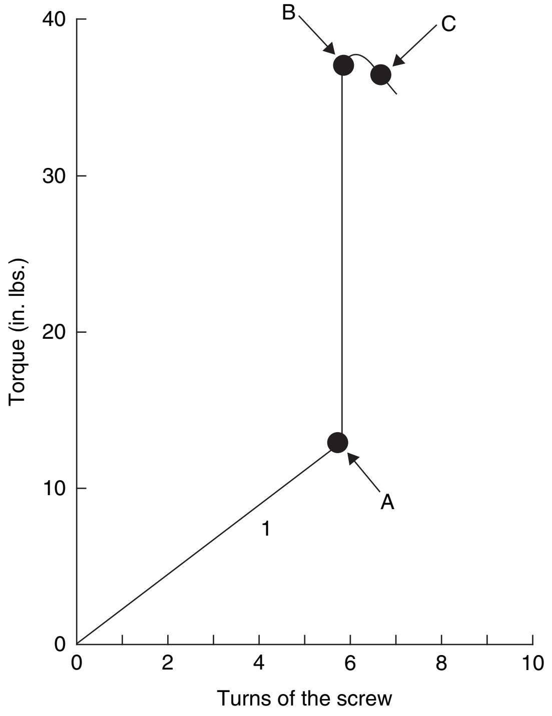


Figure 18.7. Torque variation during screw insertion.

To reduce the possibility of stripping the threads, the strip-to-drive ratio (the ratio of stripping torque to driving torque) should be maximized. To account for the slight inaccuracies of torque-controlled assembly tools (pneumatic tools ±20%, electronic tools ±3%), the strip-to-drive ratio should be about 5:1. With hand tools used by well-trained operators, a 2:1 strip-to-drive ratio is acceptable. Lubricants drastically reduce the strip-to-drive ratio and should be avoided [10, 11].

High pull-out forces within self-tapping screw connections are desirable. The pull-out force is the tensile force required to remove the screw from the boss. As mentioned earlier, pull-out force is generally higher for longer screws, but the increase is not proportional to the length of the screw. The following formulae are available to calculate appropriate dimensional needs within a chosen material. However, they are not always accurate. Hence, it is advised to test parts or prototypes directly. Generally, a material with a higher shear strength leads to better pull-out force and strip torque values [10, 11].

Stripping torque (T) and pull-out force (F) can be calculated from the following formulae:

$$T = Fr\frac{(p + 2fr)}{2r - fp}$$

where r = pitch radius of screw,
p = reciprocal of threads per unit length,
F = pull-out force,
f = coefficient of friction, and

$$F = S_s A = S_s \pi DpL$$

where S_S = shear stress; $S_S = \frac{S_t}{\sqrt{3}}$
S_t = tensile yield stress,
A = shear area; $A = \pi D_p L$,
D_p = pitch diameter,
L = axial length of full thread engagement.

18.3.7 Molded-in Threads

Molded-in threads were, for many years, the principal means of providing high-strength threads in plastics. They are still used for some applications, particularly within thermosetting resins, although the preferred system now is press-in inserts plus adhesive. Ultrasonic installation is more popular for thermoplastic resins.

Threads can be molded internally or externally into the part to be joined. Internal threads are formed using an unscrewing mechanism within the tooling, whilst external threads are molded by splitting the mold across the parting line (Fig. 18.8). Generally, coarse threads can be molded more easily than fine threads. Very fine threads are difficult to fill and are usually not strong enough to withstand the applied torque. Although the holding power of internal threads is less than that of molded-in inserts, it is greater than that of self-tapping screws, but cost implications occur when the number of holes to be threaded is high. Also, molded-in threads should only be used if the application requires infrequent assembly/disassembly [4, 8].

The roots and crests of threads should be rounded to aid in mold filling and reduce stress concentrations. As a general rule, the design of molded-in threads should leave a gap of about 0.076 cm (0.03 inches) at the edge of the screw base; threads should not extend to the edge (Fig. 18.9). The active thread length should be at least 1.5 times the pitch diameter of the thread, and internal threads require a wall thickness of at least 0.5 times the major diameter of the thread. A radius at the root is required to avoid stress concentration [4, 5, 7, 8].

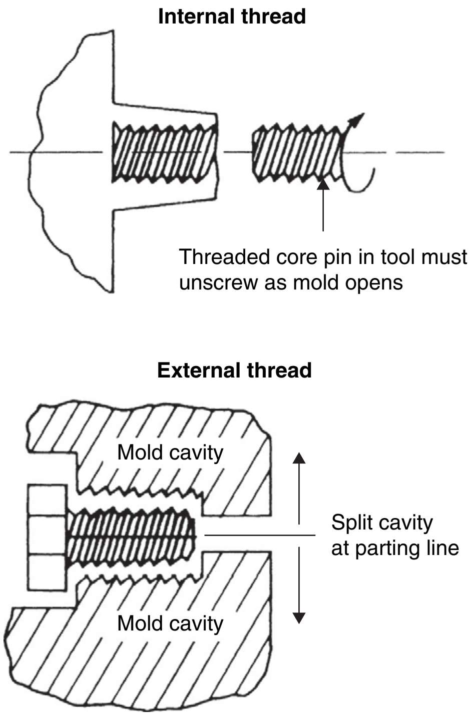


Figure 18.8. Internal and external threads.

18.4 Inserts

18.4.1 Description

Inserts are usually metal fasteners that enable assembly and disassembly of a part. Hence, in many cases, the only other alternative is a snap-fit. Inserts are also used when the engagement length available is not sufficient to get good mechanical properties of the joint. They are used for structural foam and other materials with low shear strengths that cannot withstand fastener loads alone [1, 11].

Inserts are mechanically locked into place by knurls, grooves, and slots, allowing excellent resistance to both axial and angular movement.

18.4.2 Molded-in Inserts

Inserts can be molded directly into a plastic part. This is achieved by individual placement of the insert onto pins in the mold. The plastic is then injected into the mold and it flows into the recesses of the outer dimensions of the insert, which becomes locked into place once the polymer has cooled. Molded-in inserts provide an anchor for machine screws and are commonly made from metals such as steel, brass, and aluminum. In most cases, molded-in inserts provide the highest levels of torsional and tensile resistance of any

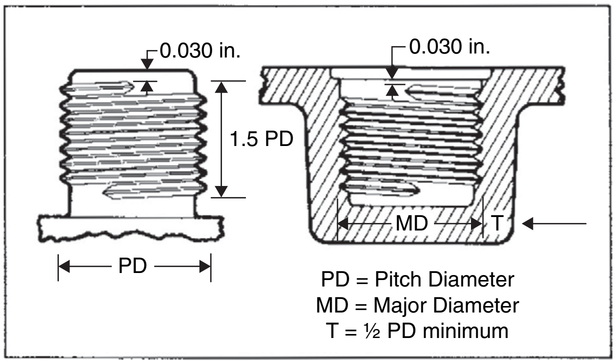


Figure 18.9. Molded-in thread design (Source: Dow Chemical).

of the inserts available on the market. They do, however, suffer high levels of residual stress when the plastic shrinks around the insert as it cools. Molded-in inserts are frequently used with thermosets and rubbers, since the stress created in these materials is lower [1, 16].

Molded-in inserts can have a smooth surface or different configurations of knurls and grooves (Fig. 18.10). Knurls can be introduced in both the longitudinal and circumferential directions. The latter contributes to a better pull-out strength but may lead to excessive stress in some plastics. Longitudinal knurls, however, increase resistance to rotation of the insert when a torque is applied [6, 11].

All sharp corners on the insert should be removed, since they can produce notches or areas of stress concentration in the plastic material; sharp corners on knurls can be removed by tumbling or grit blasting [6, 16, 17].

Molded-in inserts can have blind internal holes, or the holes can extend through the part to the other side. Blind holes are recommended for some plastics as they eliminate the risk of plastic entering the threads. Blind holes should have a spherical shape, with a rounded head.

Some molded-in inserts have deformed threads that produce a self-locking mechanism. These inserts prevent screw loosening when the part is exposed to vibrations [17].

18.4.2.1 Advantages and Disadvantages

Molded-in inserts are incorporated into the part during molding, eliminating the need for a secondary inserting operation, and no time or labor after molding is required. They provide excellent material flow between knurls, and joined parts are easily disassembled.

Disadvantages include increased stress concentration in the plastic material around the insert and increased molding cycle times, due to the necessity of stopping between cycles to position inserts in the mold cavity. Inserts can move off the pins during molding if not positioned properly and can cause damage to expensive molding equipment, in addition to generating scrap material. Plastic material can enter the threads during the molding process, making a retapping operation necessary after molding is complete. If the molding is granulated for recycling, the presence of steel inserts may cause excessive wear of granulator rotors [18].

18.4.2.2 Boss and Insert Design

Because inserts have large outer surfaces that can distribute the load placed on the fasteners over a large area, they are often attached directly to the nominal wall of the part without the use of a boss. Whether a boss is used or not, the top of the insert should extend beyond the plastic surface (Fig. 18.11) or at least be flush with the surface, in order to avoid pulling out the insert when the screw is tightened [3, 11].

Boss design for inserts is similar to that for screws. The wall thickness is the most important aspect; enough plastic material must be present around the insert to maintain high strength. Some recommended wall thicknesses for steel, brass, and aluminum inserts are a wall thickness/outside insert diameter ratio of 1.0, 0.9, and 0.8, respectively, although the recommended wall thicknesses may vary with the plastic material used [11, 15].

For applications requiring a hermetic seal, an annular space or reservoir at one end of the insert can be used to dispense a flexible sealing medium such as an RTV (room temperature vulcanization) rubber, urethane, or epoxy. Alternatively, inserts can be coated with the sealant, preferentially applied to undercut regions. Flexible sealants can more easily compensate for differences in the CTE between metals and plastics [14].

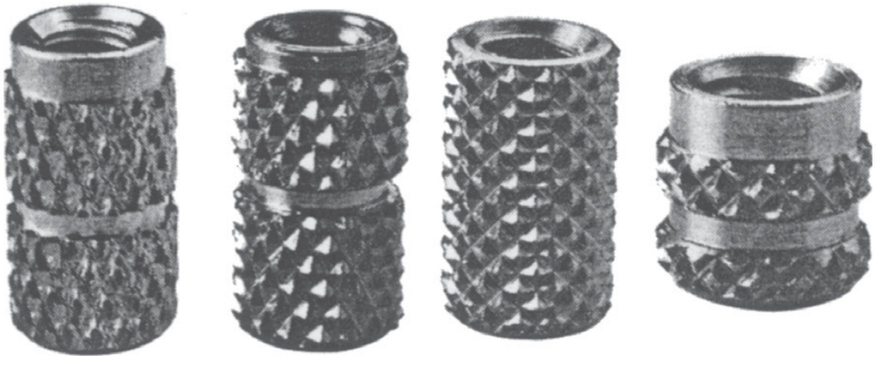


Figure 18.10. Examples of molded-in inserts.

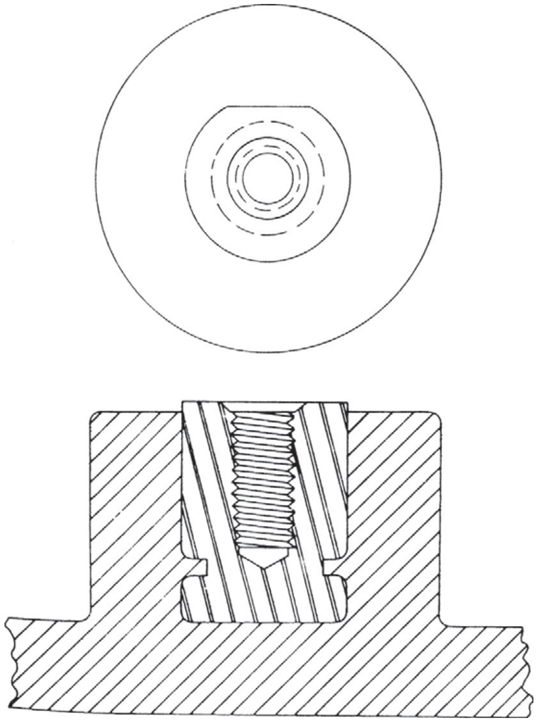


Figure 18.11. Insert and boss design.

18.4.2.3 Factors Affecting Molded-in Inserts

Foreign Substances: All parts and surfaces should be clean and no incompatible chemicals or particulate debris should be present [14].

Coefficient of Thermal Expansion: The CTE differs greatly between metals and plastics, that is, the two materials expand and contract by different amounts. Expansion/contraction of plastics is generally greater than that of a metal. Hence, areas of high stress are created around the molded-in inserts. To overcome early failure, thicker boss walls are used to compensate for these high stresses [19].

If the assembled part is likely to be exposed to thermal cycling, then molded-in inserts are not recommended for use in some plastics. If the application is likely to experience very high temperatures or subambient temperatures, brass or aluminum inserts are recommended rather than steel. This is because the CTEs are greater between plastic and steel, than between plastic and brass or aluminum. Therefore, greater thermal stresses are produced at low temperature and retention becomes an issue at high temperatures [3, 11].

Materials: Molded-in inserts perform better in semicrystalline resins than in rigid amorphous resins, such as PC, PS, and PEI, due to the higher creep associated with the material; materials with low creep are more likely to fail due to cracking [6].

Processing Conditions: Processing conditions can affect the quality of the molded-in insert. For example, the pull-out resistance of molded-in inserts can be sensitive to changes in injection pressure, injection time, and insert temperature [20].

Holding power can also be dramatically reduced when internal lubricants, such as epolene wax or calcium stearate are used in molding, even at loading levels recommended by the manufacturers [20].

18.4.3 Expansion Inserts

Expansion inserts have longitudinal slots that collapse on installation to allow the insert to enter a preformed hole (Fig. 18.12). Once in place, the insert can be expanded by using either a spreader plate incorporated into the insert, or by the action of the assembly screw. Since these inserts absorb much of the assembly force, they are used in plastics that cannot withstand a high level of stress [17, 18].

The surface configuration of the insert includes knurls and vanes. Vanes (Fig. 18.12a) are generally used for thermoplastics, and diamond knurls (Fig. 18.12b) for thermosets; the selection depends on application performance, installation requirements, and on the boss or part wall thickness. Inserts with straight knurls on the top of the insert (Fig. 18.12c) provide higher torsional resistance; inserts with a flange top (Fig. 18.12d) are used when direct contact of mating parts is undesirable [17, 18].

Expansion inserts can be metal (brass, stainless steel, aluminum) or plastic. Plastic inserts are usually made from nylon and are injection-molded [17, 21].

The advantage of expansion inserts is that they provide consistent torque values and vibration resistance, and plastic inserts will not freeze on screw threads. Assembly is rapid, and no special equipment is required for installation. The disadvantages include potentially high hoop stresses produced by screw insertion, poor flow of material between knurls, and stress relaxation of boss walls over time [11, 17, 21].

18.4.4 Thermal Inserts

Thermal inserts are heated prior to insertion into the plastic material that requires joining. The temperature of the insert softens the polymer and allows it to be pressed into a machined hole. As the polymer cools, it recrystallizes in and around the threads, securing the

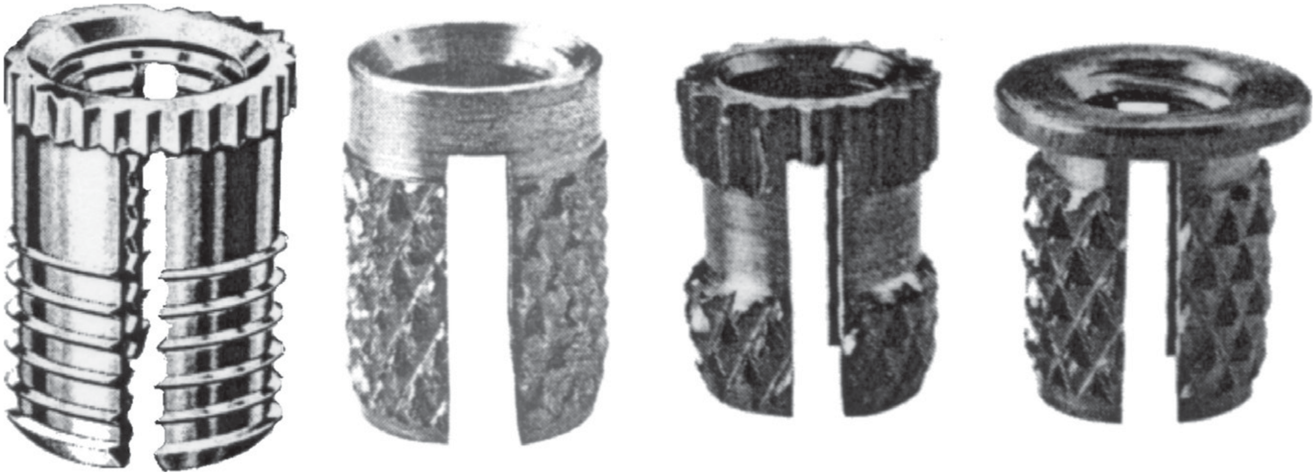

(a) (b) (c) (d)

Figure 18.12. Expansion inserts: (a) vane, (b) diamond knurl, (c) straight-knurled on the top, and (d) flange top.

insert in place. It is important not to overheat the polymer as this can lead to local plastic degradation and hence a poor joint [18].

The design of the thermal insert consists of both helical knurls and grooves. The knurls can be either unidirectional or opposed, with the opposed knurls providing a higher pull-out and torsional resistance. Traditionally, asymmetrical inserts generally provided greater pull-out resistance. However, with new advances in symmetrical designs, their performance has increased above and beyond that of traditional asymmetrical inserts [18].

As long as the temperature of the inserts is controlled, this method produces low residual stresses in the part. However, insertion is time-consuming, which increases labor costs. [11].

18.4.5 Self-tapping Inserts

Self-tapping inserts are available in both thread-forming and thread-cutting varieties, and work in the same way as self-tapping screws. Again, the thread-forming types are used in softer plastics, whilst the thread-cutting types are used in more brittle materials. An oversized hole is sized to fit the outer diameter of the insert. The insert performance is very sensitive to the tolerance in the initial hole. Once again, too large a hole leads to a loose joint, whilst a hole that is too small can lead to induced stresses and cracking. Inserts with coarse threads and longitudinal slots or notches (Fig. 18.13) cut into the plastic material, producing a corresponding thread in the plastic. These inserts provide high pull-out resistance but poor torsional resistance [18, 22].

Self-tapping inserts are easy to use and are durable due to the metal thread. They are stronger than expansion inserts, with good resistance to pull-out. However, they are only available for standard screws and provide only a limited strength improvement over plastic inserts. They are again time-consuming to fit, and hence expensive.

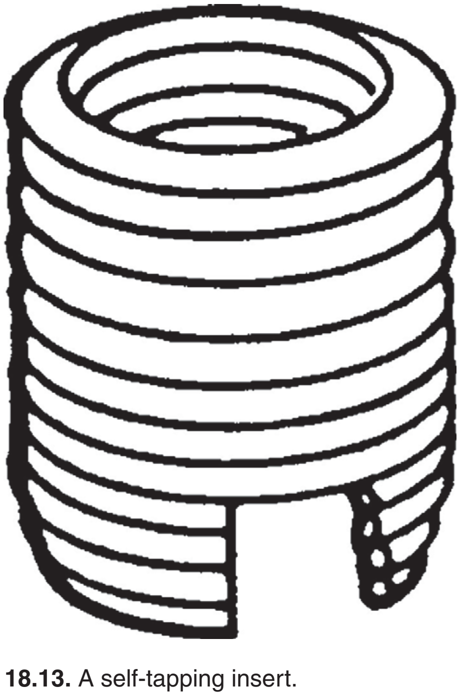


Figure 18.13. A self-tapping insert.

18.4.6 Deformation and Recovery Inserts

Inserts with vane, fin, or barbed configurations (Fig. 18.14) displace plastic material as they are driven into a preformed hole. Plastic then flows into grooves behind the barbs, providing pull-out resistance. A hex-shaped configuration also provides high torsional resistance. These inserts are most appropriate for softer thermoplastics [17, 18].

Figure 18.14. A deformation and recovery insert.

18.4.7 Ultrasonic Inserts

Ultrasonic insertion is a very repeatable and controlled process where threaded inserts are ultrasonically embedded into a thermoplastic part. The inserts are designed with undercuts, knurls, and serration, all of which provide specific torque and pull-out force (Fig. 18.15).

Installation is rapid, and high torsional strength and stability can be achieved with minimal stress build-up. In the insertion process, a hole is molded into a plastic part; the hole guides the insert in place and creates a resistance between the insert and the thermoplastic part. An ultrasonic horn is pressed against the insert, and ultrasonic vibrations create friction between the insert and the thermoplastic material. Heat generation causes the plastic to melt, and the insert sinks into the hole (Fig. 18.16). The total process time is usually less than one second [23–25].

Generally, optimum insert performance is achieved when the boss outside diameter (OD) is twice the insert diameter. The receiving hole is usually 0.38–0.51 mm (0.015–0.020 inches) smaller than the insert OD, and can be either straight or have an 8° taper (Fig. 18.17). The hole should be deeper than the insert length to provide a well for excess melt and prevent "bottoming out" of the insert. The top of the insert should be flush or slightly above the top surface of the boss. If the insert is below the surface, it could pull out of the hole as the screw is tightened, a condition sometimes referred to as "jackout" [4].

Ultrasonic insertion combines the high performance strength of a conventional molded-in insert with advantages of post-molded installation, including short cycle times, elimination of possible mold damage and down-time should inserts fall into the mold, and reduced molding cycle times. Also, low induced stress in the plastic around the metal insert results because a thin film of homogeneous melt occurs around the insert and minimal thermal shrinkage takes place. Insertion also allows multiple inserts to be driven simultaneously and is ideal for automated, high-production operations.

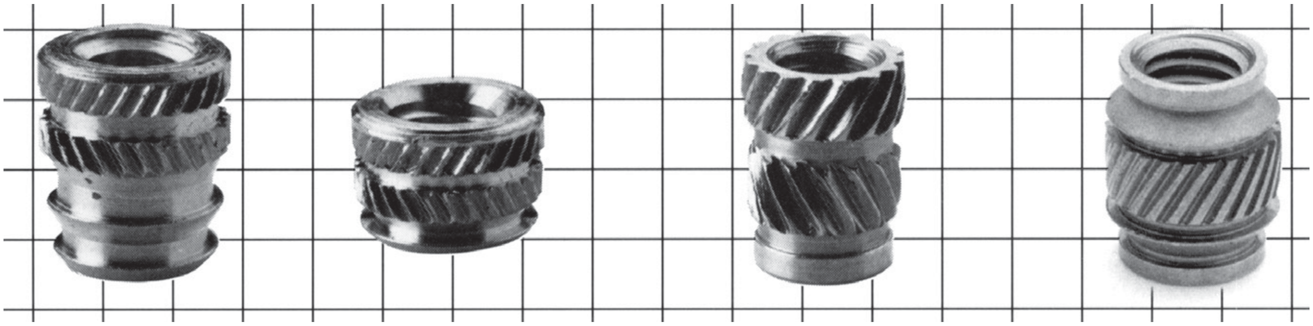


Figure 18.15. Different types of ultrasonic inserts.

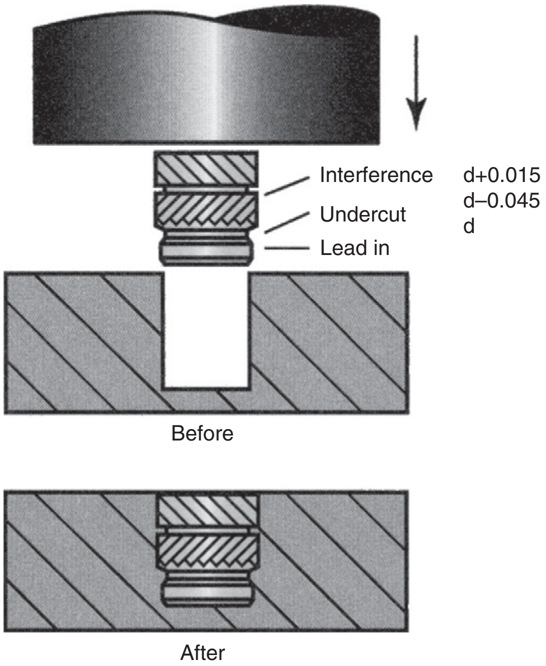


Figure 18.16. Schematic of ultrasonic insertion.

Ultrasonic insertion can be performed either by the horn contacting the insert and driving it into the plastic part, or the horn contacting the plastic part and driving it over the insert. The advantages of the latter are reduced horn wear and less noise during the assembly process. If the horn must contact the metal insert, it is advised that a hardened steel horn be used, due to the high wear of metal-to-metal contact. Although titanium horns can be used, since they have a higher tensile strength, which makes them capable of handling more stress, they are not as wear-resistant as hardened steel [25].

General guidelines for ultrasonic insertion include:

- Low amplitude to reduce horn stress
- Medium to high pressure to prevent cold pressing the inserts
- Slow speed to allow the thermoplastic to soften
- Pre-triggering to prevent a stall condition
- Horn face should be three to four times the diameter of the insert when possible to prevent horn/insert coupling.

Ultrasonic inserts are offered in brass for cost-effective applications and stainless steel for corrosive-resistant applications. Inserts available for use in tapered holes allow for rapid and accurate alignment prior to installation. Inserts for use in straight holes are provided with a self-aligning lead-in. Symmetrical inserts are also available, which can be installed into a straight or tapered hole and eliminate the need for orientation.

Typical insertion applications include eyeglass hinges, appliances, electrical housings, electrical hand tools, computer housings, television cabinets, and automotive parts.

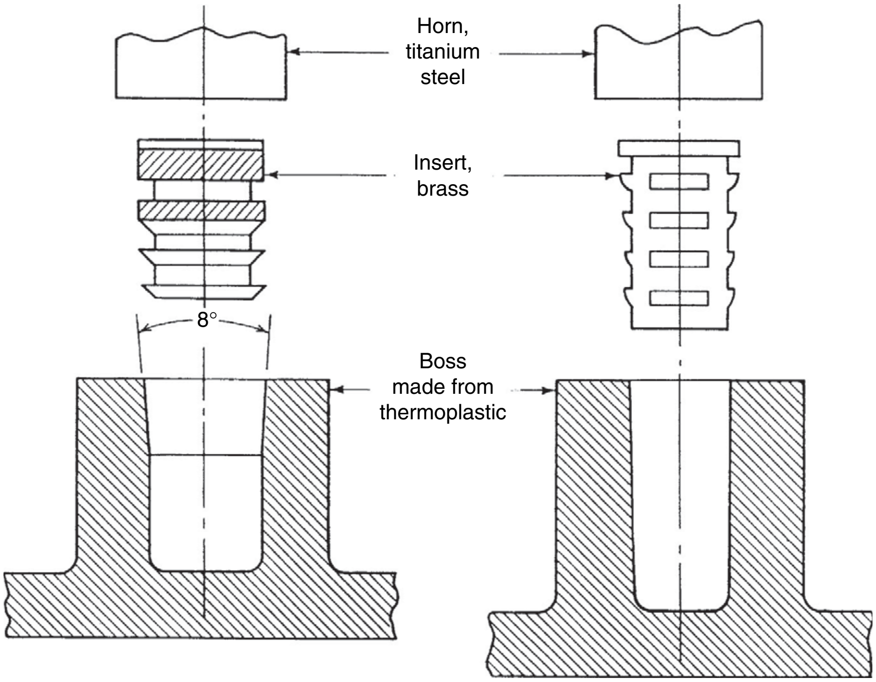


Figure 18.17. Tapered and straight holes for ultrasonic insertion.

18.5 Interference Fits

18.5.1 Description

In interference fits, also known as press fits, force fits or shrink fits, a rigid shaft is joined to a more ductile hub or boss by a dimensional interference between the outside diameter of the shaft and the inside diameter of the hub. Barbs or splines on the shaft can be used to create the interference, or "crush ribs" can be added to the inside diameter of the boss. A metal "hoop" ring at the top of the boss will prevent boss expansion, and a greater boss wall thickness will help prevent joint failure [8].

Press fitting within plastic materials can be facilitated by cooling the shaft or heating the hub immediately before assembly, in order to reduce interference. However, these types of fits should be designed with the operating temperature in mind, since differences in expansion/contraction between the hub and shaft with temperature can lead to a variance in the joint strength [6, 13].

Press fitting is economical and requires only simple tooling. It can be used to join parts of the same material as well as dissimilar materials [6, 7, 13].

18.5.2 Design

Maximum pull-out forces are obtained by creating the greatest allowable interference between the parts, which is obviously dependent on the strength of the materials used. Part geometry and design must ensure that hoop stresses produced do not exceed the maximum allowable stress for the plastic material [10].

18.5.2.1 Calculation of Interference Limits

For thick-walled cylinders, the diametral interference between a shaft and a hub can be determined from the following formula:

$$I = \frac{S_d D_s}{W}\left[\frac{W\mu_h}{E_h} + \frac{1-\mu_s}{E_s}\right]$$

where, I = diametral interference, mm (inches),

S_d = design stress limit or yield strength of the polymer, generally in the hub, MPa (psi) (A typical design limit for an interference fit with thermoplastics is 0.5% strain at 73°C (163°F)),

D_s = diameter of shaft, mm (inches),

E_h = modulus of elasticity of hub, MPa (psi),

E_s = elasticity of shaft, MPa (psi),

μ_h = Poisson's ratio of hub material,

μ_s = Poisson's ratio of shaft material.

W is a geometric factor, given by:

$$W = \frac{1+\left(\frac{D_s}{D_h}\right)^2}{1-\left(\frac{D_s}{D_h}\right)^2}$$

where D_h is the OD of the hub, mm (inches).

If the shaft and hub are of the same material, $E_h = E_s$ and $\mu_h = \mu_s$ and the above equation simplifies to:

$$I = \frac{S_d D_s}{W} \times \frac{W+1}{E_h}$$

If the shaft is a high modulus metal or other material, with $E_s > 3 \times 10^4$ MPa (4,350,000 psi), the last term in the general interference equation is negligible, and the equation simplifies to:

$$I = \frac{S_d D_s}{W} \times \frac{W+\mu_h}{E_h}$$

Maximum diametral interferences for many plastics have been calculated by the plastics manufacturers for hubs and shafts of varying diameters at particular temperatures. These values should generally be reduced by a safety factor; safety factors of 1.5–3 are appropriate for most applications. A safety factor of 1.5 is recommended for unreinforced thermoplastics, and a safety factor of 3 is normally used for reinforced polymers, which takes into account imperfections and lower strength regions arising from injection molding, such as weld or knit lines [10, 26].

18.5.2.2 Reduction of Stress Concentrations

The high stresses produced in press fit assembly can make the parts more susceptible to chemical and thermal attack. To reduce stress concentrations, parts and inserts should be clean and free of all incompatible chemicals. Inserts with smooth, rounded surfaces will result in lower stress concentrations than knurled inserts, and parts that are being inserted should not be located near knit lines [4, 6, 7].

18.5.3 Stress Relaxation

In a viscoelastic material under constant strain, such as in press fits, stress gradually decreases over time.

This phenomenon reduces the joint strength of the assembly, and a press fit that was initially acceptable could loosen or fail completely. The amount of stress relaxation depends on the properties of the polymer used, and can be affected by the presence of fillers, additives, reinforcements, pigments, and lubricants, the initial stress in the part, and the environmental conditions (temperature, humidity, etc.) [10].

The effect of stress relaxation can be reduced by the incorporation of grooves or knurls on the shaft. Creep that does occur over time results in the plastic cold-flowing into the grooves, so that the strength of the press fit is retained [7].

18.6. Snap-fits

18.6.1 Description

In snap-fit fastening, two parts are joined through an interlocking configuration that is molded into the parts. Many different configurations are possible to accommodate different part designs. In snap-fits, a protrusion on one part (hook, stud, bead) is briefly deflected during joining to catch in a depression or undercut molded into the other part. The force required for joining varies depending on the snap-fit design. After the brief joining stress, the joint is vibration-resistant and usually stress-free [4, 7, 27].

Snap-fits are among the most economical, rapid, and popular assembly methods, and their use is increasing due to the trend toward elimination of separate fasteners in order to simplify manufacturing costs. Snap-fits can be used to join dissimilar plastics or plastics to metals, and can be designed for permanent fastening or for repeated disassembly. A wide range of snap-fit designs exist from pen caps, bottle caps to removable automotive components.

Hermetic or moisture-resistant seals are possible in some designs. Snap-fits require more attention to engineering design than some other mechanical fastening methods, and can fail before or during assembly, or during use, if not designed properly. Stress analysis of some snap-fit designs can be performed using hand calculations; designs with more complicated geometries may require finite element analysis for accurate results [28].

18.6.2 Advantages and Disadvantages

Snap-fits do not require the introduction of additional materials such as adhesives, fasteners, or bolts, making them lower in cost and easier to assemble, leading to higher production rates (up to 60 parts per minute) and, in many cases, minimal tooling. Snap-fits are excellent for the joining of dissimilar materials such as metal to plastic. They can be designed as a permanent fastening device, often inaccessible from the outside of the part, or can be designed for repeated disassembly.

Snap-fits are vulnerable to fracture due to fatigue and are impossible to repair, often resulting in complete failure of the part. Snaps-fits, therefore work best with more ductile materials but can still suffer from loosening through thermal expansion, moisture uptake, and environmental effects.

18.6.3 Types of Snap-fit

There are two main types of snap-fit: the cantilever beam and the cylindrical (annular) snap-fit. Other snap-fits include torsional, ball-and-socket, U-shaped, bayonet finger, snap-on or snap-in and the combination snap-fit.

18.6.3.1 Cantilever Beam

Cantilever beam snap-fits consist of a hook-and-groove joint in which a protrusion from one part interlocks with a groove on the other part (Fig. 18.18). The design of the beam can permit great flexibility to suit the material being joined, resulting in a tight fit with low stress induced into the system. This snap-fit design is the most common; it is easy to assemble, provides good retention, and is usually stress free [10, 28].

18.6.3.2 Annular

Annular, or cylindrical, snap-fits are used to join spherical or elliptical parts, such as pens and bottles with caps. One of the parts contains a lip or protrusion around the part circumference that engages with a protrusion or a groove on the mating part (Fig. 18.19). After assembly, parts are stress-free. Multiaxial stresses are produced during annular snap-fit assembly, making design calculations difficult.

18.6.4 Materials

The properties of materials used in snap-fit designs affect the performance of the part. UV stabilizers may

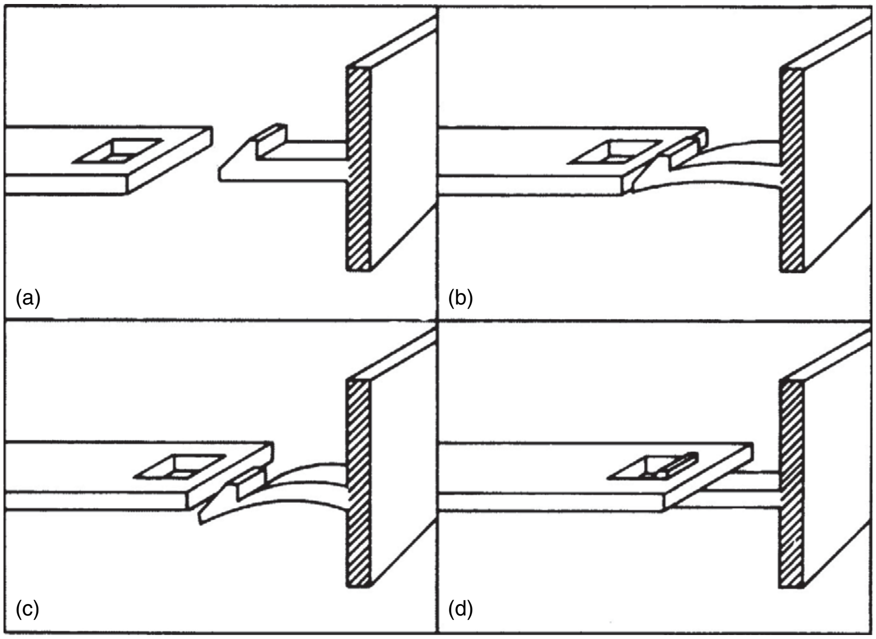
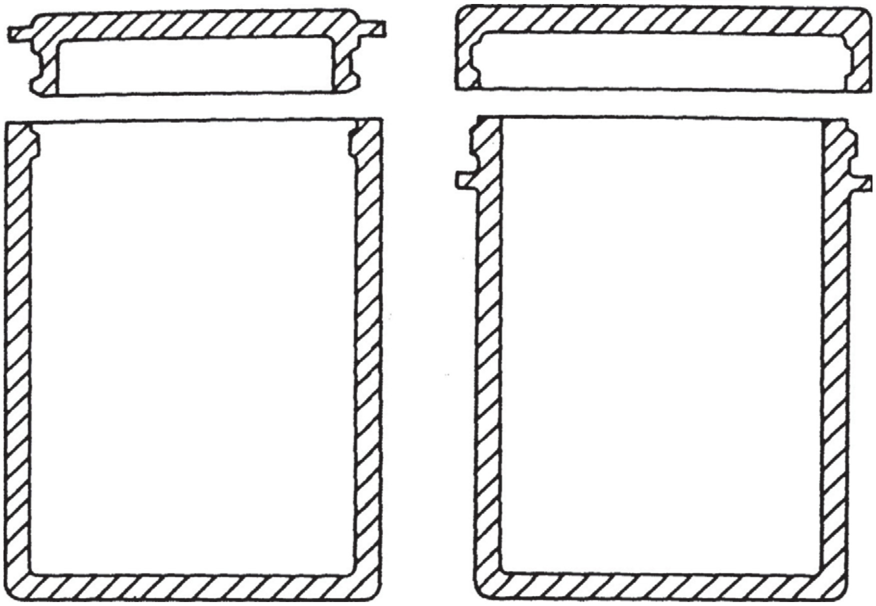


Figure 18.18. A cantilever beam snap-fit: (a) cantilever beam and mating piece before assembly, (b) latch is partially deflected as initial contact is made, (c) latch approaches maximum deflection, and (d) latch locks into the hole in the mating part and returns to its undeflected position.



(a) Designed with protrusion from nominal wall

(b) Designed with groove in nominal wall

Figure 18.19. Annular snap-fits.

be required to provide color retention in the presence of sunlight, in order to maintain aesthetic quality and preserve mechanical properties.

Temperature changes may cause two dissimilar snap-fit components to expand/contract at different rates, depending on the respective CTEs. Rates can vary by a factor of 2 for dissimilar plastic components and between 5 and 10 for plastic/metal components. The operating temperature of the snap-fit should therefore be considered in the design [28, 29].

18.6.5 Design

Materials used in snap-fits should have high stress-crack resistance, especially in chemical environments. Only materials with small percentages of regrind should be used in snap-fits, since regrind can reduce the mechanical properties of the plastic [28].

Some guidelines for designing snap-fits are (Fig. 18.20):

- When multiple snap-fits are used, snap engagements should oppose each other (Fig. 18.20a).
- Supports or guides around the perimeter of mating parts eliminate shear loading on the snap, which should work only in one direction (Fig. 18.20b).
- Each snap should be designed with only one flexible member (Fig. 18.20c).
- Maximizing snap engagement minimizes the influence of tolerances and allows for engagement edge wear with use (Fig. 18.20d).
- A deflection-limiting backup can be used to prevent overstraining during insertion or removal (Fig. 18.20e).
- When impact properties are important, stiffness of the snap should be over-designed. Disengagement forces can exceed 900 times the weight of the mating parts (Fig. 18.20f).

18.6.5.1 Mold Considerations

Ease of molding should be considered in the design of snap-fits. Some snap-fit designs require complicated and, therefore, expensive molds; however, designs can often be modified to allow the use of simpler molds. Figure 18.21a shows a cantilever hook or latch design that requires an undercut in the mold (Fig. 18.21b). Removal of the part from the mold without damaging the hook is difficult. Molds with collapsible cores or slides that retract the steel that is used in forming the undercut after molding can be used, but they are expensive. An alternative snap-fit design in which the hooks face outward from the part (Fig. 18.21c) results in an easy removal of the part from the mold and reduces mold complexity and cost. A second alternative would be to include a hole in the part wall under the hook for tool relief (Fig. 18.21d) [27].

18.6.5.2 Cantilever Snap-fits

A cantilever beam design with a constant rectangular cross-section is shown in Fig. 18.22. The amount of beam deflection and the forces involved in deflection and assembly can be calculated using equations based on a linearized simplification of the partial differential equation known as Castigliano's second theorem:

$$y = \partial U / \partial P$$

where y is the deflection, U is the flexural energy of the beam, and P is the deflection force.

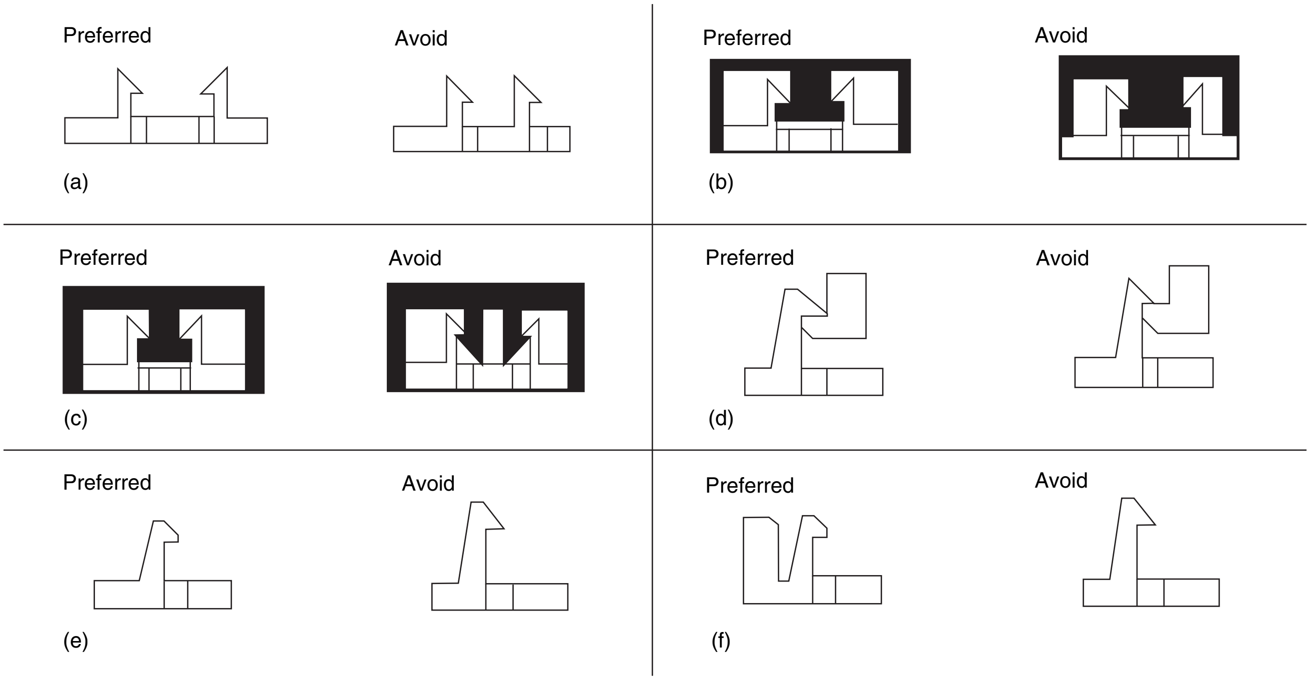


Figure 18.20. Snap-fit designs.

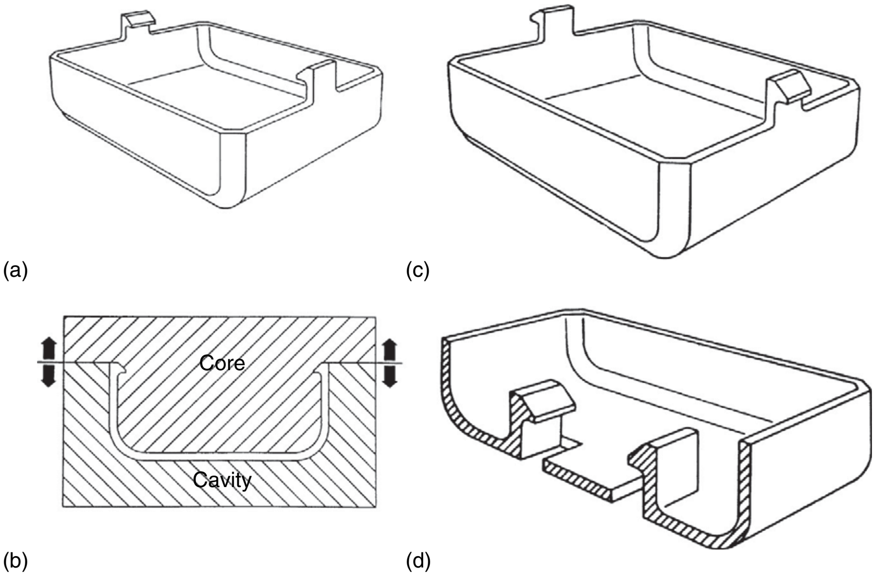


Figure 18.21. Mold considerations in snap-fit designs: (a) cantilever snap-fit design that requires an undercut in the mold, (b) mold with undercut for the design in (a), (c) modified design where the latches face outward, and (d) modified design where tooling holes in the part wall simplify the mold design and the part can be ejected easily.

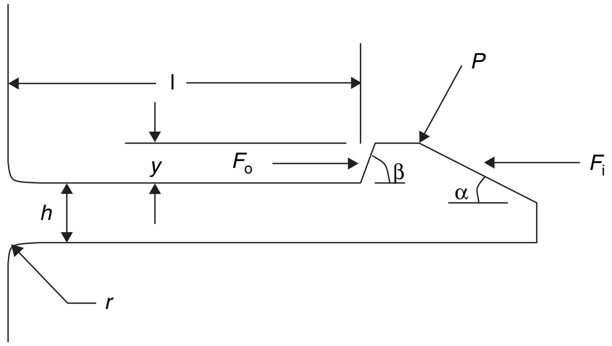


Figure 18.22. Cantilever snap-fit (Source: TWI Ltd).

Classic cantilever beam theory assumes that the beam base is rigidly fixed and deflection is due only to bending stress [7, 30].

18.6.5.2.1 Permissible Deflection

In Fig. 18.22, the permissible deflection of a rectangular cantilever beam of constant thickness, equal to the height of the undercut (y), is dependent on the thickness (h) and length (l) of the beam and the permissible or maximum strain of the material (ε) [7]:

$$y = \frac{2}{3}\frac{\varepsilon l^2}{h}$$

Therefore, materials that can withstand higher levels of short-term strain can be deflected further without damage; damage is expressed as residual deflection, the percentage of the initial deflection that remains after deflection is complete. For a single, momentary deflection, partially crystalline materials can be stressed to levels very near to the yield point; amorphous plastics may be stressed up to around 70% of the yield strain. Permissible strain for glass fiber reinforced materials, which do not usually have a distinct yield point, is about half the elongation at break value. Specific values for permissible strain are normally available from the material manufacturer. Permissible strains for repeated assembly and disassembly are lower than that for permanent assembly (around 60% of permanent assembly values). However, since most material damage occurs after the initial deflection, applying a safety factor to the single-assembly data can result in a reasonable estimate of repeated assembly/disassembly snap-fit performance [4, 7, 27].

The value obtained for the permissible deflection should not be exceeded during either ejection from the mold or part assembly. Permissible deflection of a constant thickness beam can be increased by increasing the beam length or decreasing the thickness; an increase in length is more effective due to the squared term in the equation. Generally, deflection should be less than or equal to 0.5 times the beam length [7, 27].

If the equation for permissible deflection is rearranged, maximum strain (ε) can be calculated for a particular undercut or deflection. If the strain is too high, a decrease in beam thickness or deflection or an increase in beam length will lower it to acceptable levels. The ratio of beam length to beam thickness is important in the determination of permissible strain; as the length/thickness ratio decreases, the allowable or permissible strain for the particular cantilever beam increases. A typical length/thickness ratio used in cantilever beams is 5.4 [27].

18.6.5.2.2 Deflection Force

The deflection force (P) required to bend the cantilever by a deflection equal to the height of the undercut (y) can be calculated from the cantilever geometry and the secant modulus of the material (E_s):

$$P = \frac{bh^2}{6} \times \frac{E_s \varepsilon}{l}$$

in which b equals the beam width at the base. The width is perpendicular to the plane of the applied force [7].

The secant modulus is the ratio of stress to strain at a point on the stress-strain curve corresponding to a particular strain (Fig. 18.23). Its use in beam theory calculations instead of the elastic or tangent modulus (E_o) results in more accurate estimates of deflection and stress in momentary, high-stress applications. Due to the nonlinearity of the stress–strain curve for plastics, use of the elastic modulus predicts that the material will be less flexible, and therefore will deflect less than it actually does during assembly. The strain used to determine the secant modulus should be the permissible strain (ε) used to determine the permissible deflection. If straining the material beyond the linear region of the curve is not recommended, or if stress/strain data are not available for the design conditions of the beam, the elastic or flexural modulus should be used in calculations [7].

18.6.5.2.3 Engagement Force

The engagement or assembly force (F_i in Fig. 18.22) is the force required to engage the snap. It is dependent on the deflection force, the lead-in angle (α) of the latch or hook, and the coefficient of friction (μ) of the plastic material:

$$F_i = P\left[\frac{\mu + \tan\alpha}{1 - \mu\tan\alpha}\right]$$

Values for the coefficient of friction depend on the assembly speed, the pressure applied during assembly, and the surface quality of the parts. The rougher the surface, the higher the coefficient of friction [7].

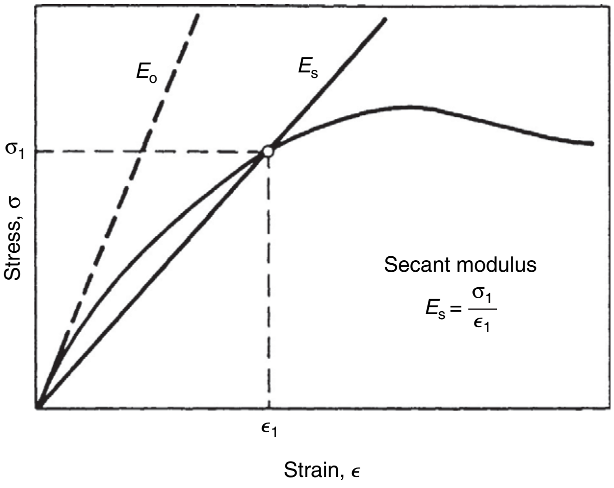


Figure 18.23. Determination of the secant modulus from a stress–strain curve.

18.6.5.2.4 Disassembly Force

When designing the snap-fit for disassembly, the disassembly force can be calculated using the same equation as the engagement force, with the return angle or pull-out angle β (Fig. 18.22) used instead of the lead-in angle. Angles can be varied to increase or decrease the force necessary for assembly or disassembly; the smaller the lead-in (or return) angle, the lesser the force required for assembly (or disassembly). As the return angle approaches 90°, the snap-fit becomes more self-locking. Angles can be adjusted so that the assembly or disassembly force is greater than, equal to, or less than the deflection force [7].

18.6.5.2.5 Stress Concentration

Stress contours of a constant cross-section cantilever beam obtained from finite element analysis (Fig. 18.24a) show that stress is not equally distributed but is concentrated at the root. To reduce the stress concentration in this region, which can lead to joint failure, the root radius can be increased (Fig. 18.25), or a rib can be added to the design.

Figure 18.25 shows the effect of increased root thickness on stress concentration. Although the optimum root radius/height ratio appears to be 0.6, use of this radius would produce a thick area at the intersection of the beam and the part wall, which may lead to sink marks and/or voids. To avoid this, the thickness should be no more than 50–70% of the nominal wall thickness; testing indicates that the radius should not be less than 0.38 mm (0.015 inches) [3, 10, 27].

18.6.5.2.6 Tapered Cantilever Beams

Stress can also be distributed more evenly by tapering the beam from the root to the tip (Fig. 18.24b). Molded cantilever beams can be tapered in the plane of the applied force (height or thickness) or perpendicular to the plane of the force (width); more flexibility can be achieved when the thickness of the beam is tapered. A tapered beam (Fig. 18.26) is more compliant than a

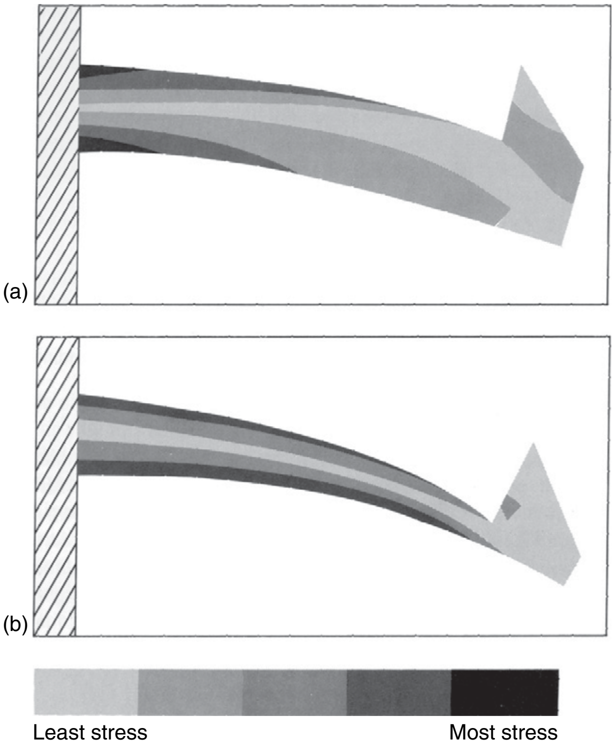


Figure 18.24. Stress contours of cantilever beams obtained from finite element analysis: (a) beam of constant thickness, and (b) tapered beam.

straight beam with a similar deflection and assembly force. Tapering the beam thickness to half that of the base increases the permissible deflection by over 60% of that of a straight beam. A 50% taper is optimal, a compromise between the thick base sections that produce residual stresses and thin tips that are difficult to mold and that break during snap-fit assembly [27].

Cantilever beam equations for tapered beams must be modified to account for the change in geometry. To avoid integrating differential equations for every design, proportionality constants (K) have been calculated for varying tip/base ratios. The modified equation for permissible deflection in the most common tapered beam (50% in thickness or height) then becomes [4, 30]:

$$y = 1.09\frac{\varepsilon l^2}{h}$$

Proportionality constants are useful only when either thickness or width varies, not both. Equations for cantilever beams of other cross-sections and tapers can be found in Reference 4.

18.6.5.3 Annular Snap-fits

Assembly forces in annular snap-fits are complicated, since the snap-fitting bead on the shaft expands a relatively large portion of the hub or tube during assembly; assembly stresses are therefore distributed over a large area of material. Elasticity of the hub and shaft is important in annular snap-fit design. Generally, the shaft is considered to be rigid and the hub elastic, although other designs, such as an elastic shaft and rigid hub or shaft and hub of equal flexibility, are also possible [4].

The wall thickness of an annular snap-fit should be uniform to avoid stress risers. The ideal shape is circular; shapes that deviate from a circular geometry are more difficult to eject from the mold and assemble. Weak spots produced by weld lines, gate turbulence, or voids during molding can cause cracking of the undercut during assembly. Weld lines can be avoided by changing the design or moving the gate; if this is not possible, a bead or rib can be used to strengthen the section near the weld line [10].

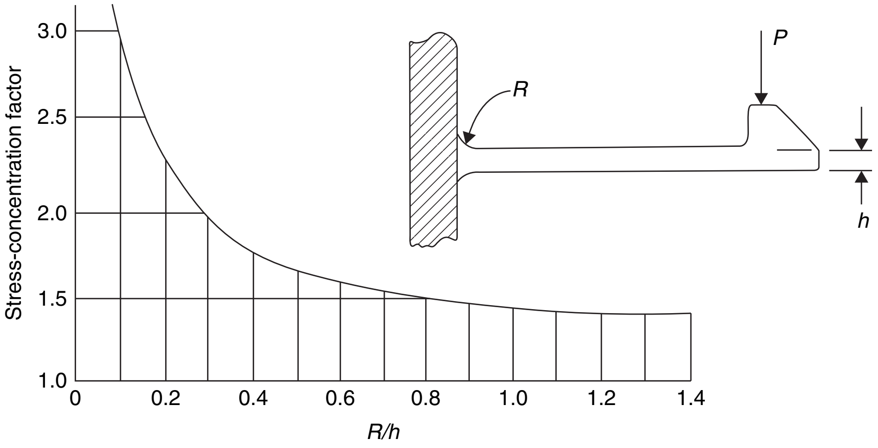


Figure 18.25. Effect of ratio of root radius to beam thickness on stress concentration in a cantilever beam.

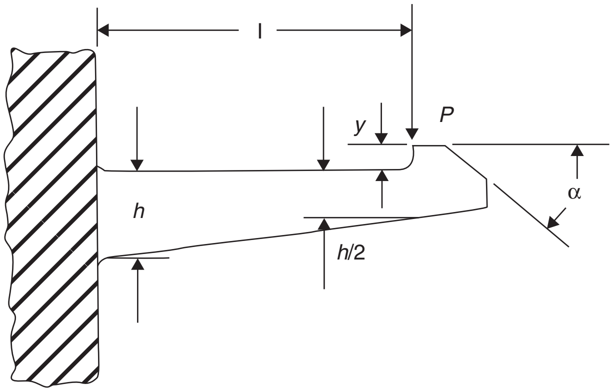


Figure 18.26. Cantilever beam with a 50% taper in thickness.

If the assembly will not be subjected to a significant axial load, slots can be used in the snap-fit. These permit the use of a deeper undercut and groove and are useful for parts requiring frequent assembly and disassembly; however, slotted snap-fits have lower retaining forces. An example of a slotted snap-fit is shown in Fig. 18.27.

18.6.5.3.1 Permissible Deflection

The maximum undercut or deflection in annular snap-fits (*y*) is dependent on the maximum strain of the material (ε_A) and the diameter of the hub or tube (*d*):

$$y = \varepsilon_A d$$

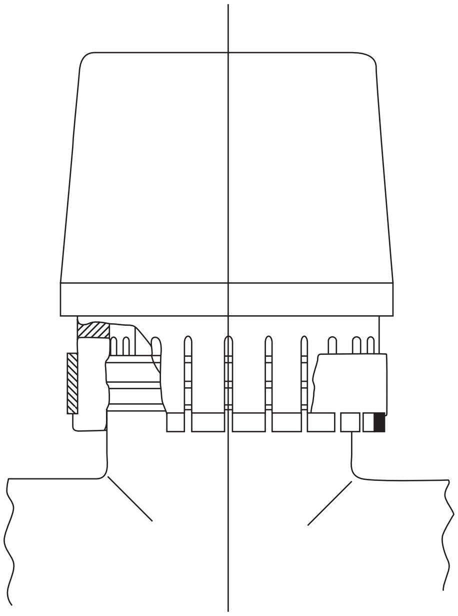


Figure 18.27. Example of a slotted snap-fit: a thermostat body joined to a radiator valve, using a metal ring to ensure retention (Source: DuPont).

The permissible undercut should be reduced by 50% to account for the cylindrical shape (Fig. 18.28) [4].

Annular snap-fit joints can be permanent or designed for easy disassembly, depending on the dimension of the bead and the return angle. Permanent, inseparable designs require split-cavity molds for part ejection [4].

18.6.5.3.2 Deflection Force

The deflection force (*P*) for joints near the end of the hub depends on the undercut (*y*) the joint diameter (*d*) the secant modulus of the material (E_s) and a geometric factor (*X*) which accounts for the rigidity of the component materials:

$$P = ydE_s X$$

Equations and diagrams for determination of the geometric factor can be found in Reference 4.

18.6.5.3.3 Engagement Force

The engagement or assembly force (F_i) is similar to that of cantilever beams:

$$F_i = P\left(\frac{\mu + \tan\alpha}{1 - \mu\tan\alpha}\right)$$

where μ is the coefficient of friction of the material and α is the lead-in angle [4].

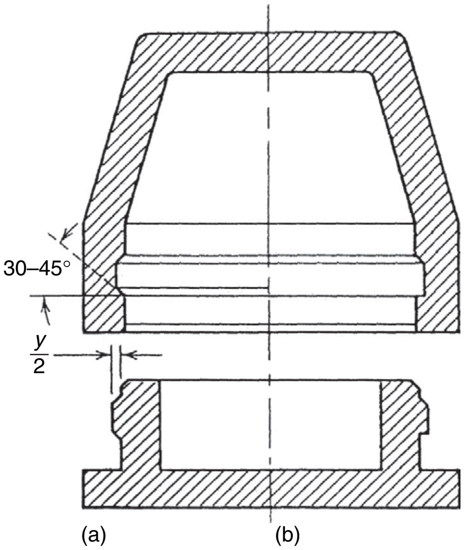


Figure 18.28. Annular snap-fit: (a) separable and (b) permanent.

18.7 Rivets

18.7.1 Description

Rivets are a type of semipermanent mechanical fastener. They consist of a smooth cylindrical shaft with a head at one end. The end opposite to the head is referred to as the bulk-tail. They are installed by placing them into a predrilled hole and then the tail section is deformed, so that it expands to 1.5 times the original shaft diameter. Clearance around the rivet shaft should be wide enough for easy insertion, but low enough to prevent slippage of the assembled parts. Common rivet heads are shown in Fig. 18.29. Although rivets are mainly used to join metals, they have also shown success in joining plastics.

Rivet fastening can introduce high stresses in plastic parts. The larger the rivet head, the lower the stresses as the load is distributed over a larger area. A washer under the flared end of the rivet also reduces high, localized stresses. Shouldered or aluminum rivets, which deform under high stress, limit the amount of force that can be applied to the part. In order to control the compressive stresses the operator needs to ensure that the setting tool is calibrated to the correct length [5, 6].

Plastic rivets, such as the Marson PR-75K, are also available. These are precision molded from nylon and are used to join plastic to plastic, fiberglass, or metal. This product offers a high performance, low-weight alternative in line with the demands in the automotive and aerospace industries.

18.7.2 Advantages and Disadvantages

Rivet fastening is more cost-effective than threaded fasteners due to their large volume, high-speed assembly. Rivets are also less susceptible to vibrational loosening than screws and bolts.

However, rivets have lower tensile and fatigue strengths than bolts and machine screws, and less precision in part size due to high volume manufacture. Rivets can also cause part cracking, and loose assembly is a common fault but it can be corrected by using a shorter rivet or a thicker washer [1].

18.8 Staking

18.8.1 Description

Staking is a process that is specially suited to connecting parts made from dissimilar materials (e.g., plastic to metal). The plastic part is provided with a protrusion that fits through a hole in the other part. The protrusion is then deformed through cold flow or melting of the plastic to form a head that mechanically locks the two components together (Fig. 18.30). Staking is a quick and economical technique and has the advantage that no consumables, such as rivets or screws, are required. Staking can only be used to join thermoplastics; PS, ABS, SAN, acrylic, PC, PA, acetal, PPO, PP, PE and PSO are commonly used for staking [31].

18.8.2 Advantages and Disadvantages

Staking can be used to join dissimilar materials as long as one of the materials is a thermoplastic. Assembly by staking is rapid, the materials can be disassembled for recycling, and the cost of tooling is low. However, loosening can become an issue in relation to the difference in the CTE of the materials being joined.

Other disadvantages of this joining method are that the fastening is permanent, and the joint is not always aesthetically pleasing.

18.8.3 Cold Staking

Cold staking, also referred to as heading, uses high pressures, beyond the yield strength of the plastic, to cause it to deform into the shape of the head. This form

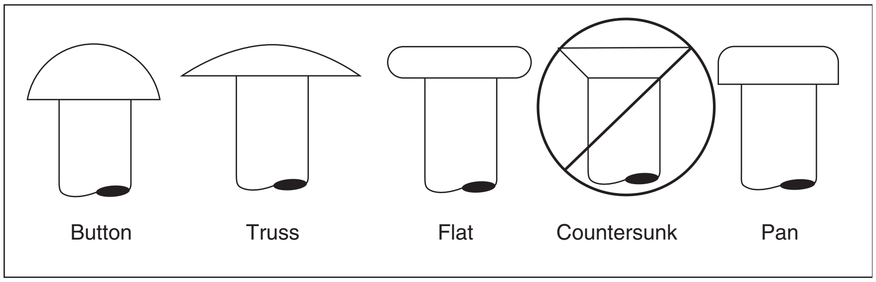


Figure 18.29. Commonly used rivet heads. Countersunk heads should be avoided for use with plastic materials.

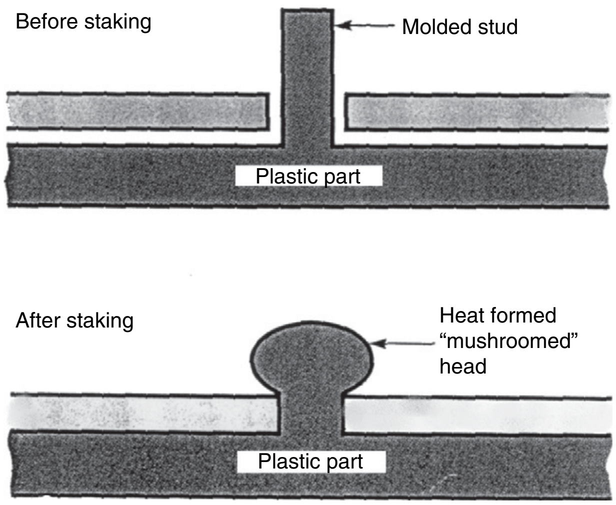


Figure 18.30. Principle of staking.

of staking is most suitable for highly malleable thermoplastics, such as acetal and nylon, and not brittle or fragile materials, since the pressure generally causes too much damage with these types of material [31].

Processing considerations in cold staking include a good fixture support under the part wall opposite the stud, use of a positive stop on the staking press to prevent damage to the parts, a large radius at the stud base to eliminate shear stress, close hole size tolerance to prevent collapse, and careful material selection. Cold staking is not generally used when a tight assembly is necessary [31].

18.8.4 Heat Staking

Heat staking involves the use of heated probes and light-to-moderate pressure to compress and reform the stud. It is an economical process that produces consistent results, and stresses produced are lower than in cold staking [31].

A number of factors are important in heat staking design:

- Stud diameter, which depends upon the material and its moldable wall thickness; ABS and PC stud diameters are typically 1–2 mm (0.04–0.08 inches). Diameters of 2–6 mm (0.08–0.24 inches) are common for structural foam.
- Height of the stud above the mating piece—should be about 1.5–3 times the stud diameter.

Appropriate probe, stud, and stud head geometries (Fig. 18.31) also vary with the application requirements. Flat tip probes are the easiest to make and maintain. If cosmetic appearance of the stud head is important, dimple probes can be used; these probes require a machined recess in the probe tip. A cross-shaped stud or hollow boss is recommended for high-strength retention and to minimize sink marks in the front surfaces from injection molding large studs or thick wall sections. If the boss hole is needed for other attachments such as self-tapping screws or inserts, a rosette shaped probe tip can be used to flair out the hollow boss.

It is essential to control processing variables for good results in heat staking. These variables include temperature, pressure, and cycle time.

The temperature of the staking tool depends on the plastic being formed. Typical pressures are ≤7MPa (1000 psi), and cycle times generally range from 1 to 5 seconds [31].

An example of a heat staking machine is shown in Fig. 18.32.

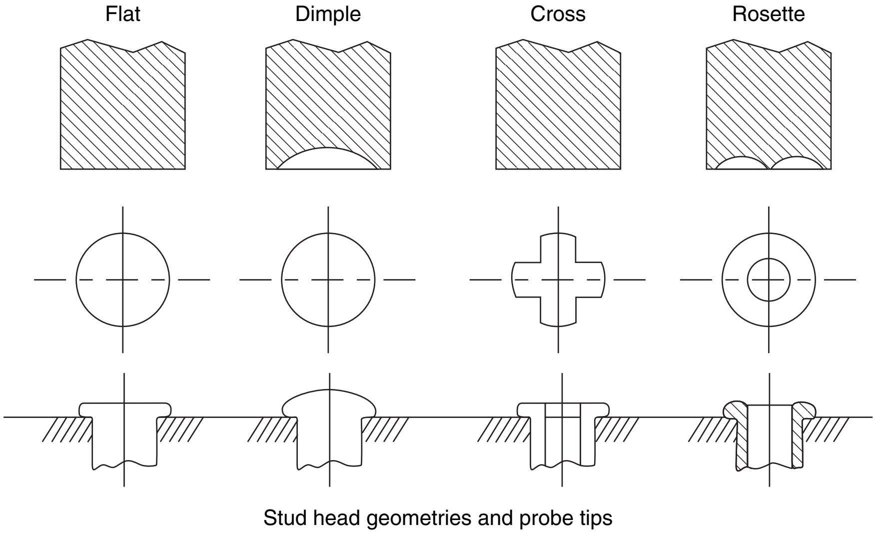


Figure 18.31. Stud head geometries and probe tips.

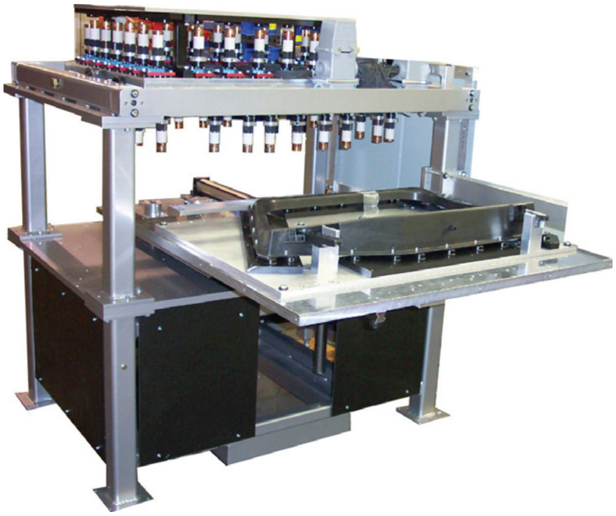


Figure 18.32. Jeep Wrangler 4-door heat staking system (Source: Thermal Press International).

18.8.5 Hot Air Staking

In hot air staking, also known as thermo-pneumatic staking, thermostaking or hot air/cold staking, heat is applied to the stud by means of a stream of hot air, which is delivered through a tube, either directly above or to the side of the stud (Fig. 18.33). Once the stud has melted or softened, a cold stake probe descends onto the stud and compresses it. A stud head is formed and, after the plastic solidifies and cools, the cold staking probe is retracted. The design of the cold stake probe influences the final shape of the stud heads making them domed, split, knurled, or flared. A number of stud heads can be hot air staked at the same time, even if there is variance in size, height, or shape [18, 31, 32].

18.8.6 Ultrasonic Staking

In ultrasonic staking, a thermoplastic stud is melted using ultrasonic energy and reformed to mechanically lock another dissimilar material in place. Advantages of ultrasonic staking include short cycle times (typically less than 2 seconds), tight assemblies with virtually no tendency for recovery, repeatability, and design simplicity.

Ultrasonic staking works well with soft or amorphous materials having low melt flows, allowing the head of the rivet to form by both mechanical and thermal mechanisms. With high-melt materials, or materials that require high vibrational amplitudes, melt can flow so rapidly that is it ejected out of the horn contour, resulting in an incomplete rivet head [33, 34].

Part design for staking is dependent on the materials being assembled, the required strength of the assembly, the loading (tensile, shear) that the stake must resist, the importance of cosmetic appearance, whether stakes are recessed in the part, and whether or not multiple staking is necessary. Proper stake design results in optimal strength with little or no flash. A high amplitude horn, minimal initial contact area between the horn and stud, and light initial contact force with controlled horn descent velocity concentrates ultrasonic vibrations in a localized area, resulting in a rapid melt and short cycle time. A slow actuator downspeed prevents stud fracture and allows melted material to flow into the horn cavity, and a higher hold force results in increased strength. Pretriggering (beginning ultrasonic vibrations before the horn touches the stud), results in the creation of an out-of-phase wave and prevents horn/stud coupling. The method requires the stud to be properly located and rigidly supported from

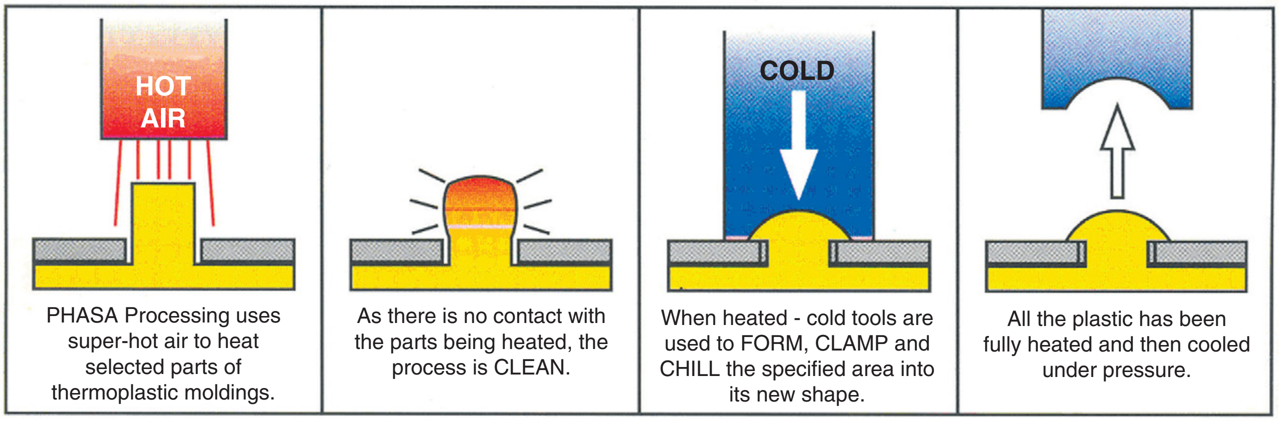


Figure 18.33. Schematic displaying the basic principles of hot air staking (Source: Phasa Ltd).

beneath to ensure correct alignment with the horn cavity, and that energy will be expended at the horn/stud interface, rather than exciting the entire plastic assembly and fixture. Several designs are described below [23–25, 34].

The standard rosette profile stake (Fig. 18.34) is used for studs with diameters of 3.2–4.0 mm (0.125–0.156 inches). The top of the molded stud is flat, and melting begins at the extended point in the horn cavity. The head produced is twice the stud diameter and satisfies the requirements of the majority of staking applications. Standard profile stakes are used for nonabrasive (unfilled) thermoplastics and should not be used for studs more than 4.0 mm (0.156 inches) in diameter [34].

A dome stake (Fig. 18.35) is recommended for 3.2 mm (0.125 inches) diameter studs or less, when multiple staking is performed where horn alignment can be a problem, or for glass- or mineral-filled materials. Melting is initiated at the top of the tapered (cone shaped) stud, the point of which initiates material melt, reducing energy being transmitted through the stud. The tip and the part will self-align, making alignment less critical than with the standard profile, and the stake has a good cosmetic appearance. The dome staking tip is less susceptible to wear from abrasive materials than the standard profile stake and, if necessary, can be redressed more easily than staking cavities using the inverted staking cone [34].

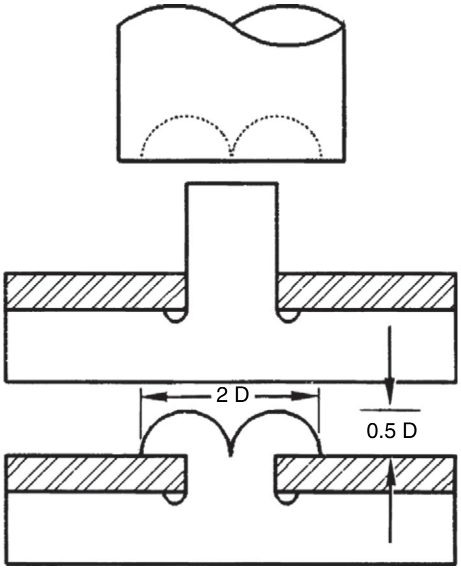


Figure 18.34. Standard profile stake used in ultrasonic staking. The unshaded area is a thermoplastic, the shaded area is a dissimilar material, usually metal (Source: Branson Ultrasonics Corp.).

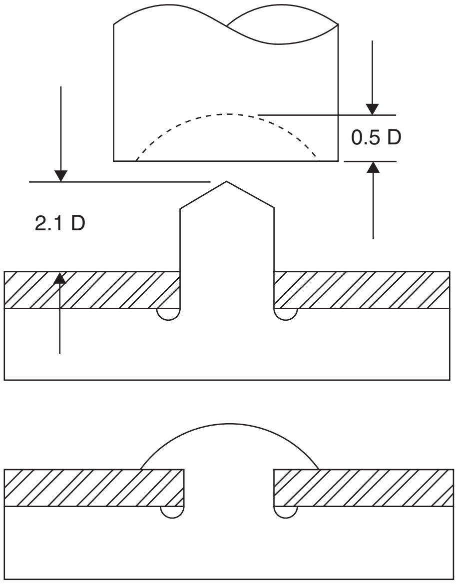


Figure 18.35. Dome profile ultrasonic stake (Source: Branson Ultrasonics Corp.).

Low-profile staking (Fig. 18.36) is similar to standard-profile staking, but differs in the height of the finished staked head. This reduction in head height shortens the cycle times and is advantageous when space is limited; however, it produces a lower strength stake [34].

A knurled stake (Fig. 18.37) is simple, and can be rapidly assembled with a hand-held welding tool; it is used with all thermoplastics when appearance and strength are not critical. There is no dimensioned horn

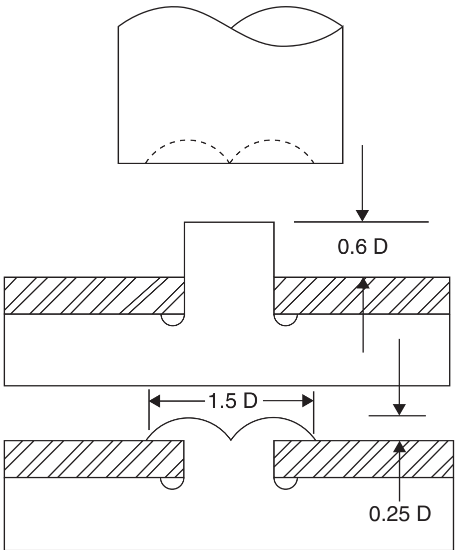


Figure 18.36. Low-profile ultrasonic stake (Source: Branson Ultrasonics Corp.).

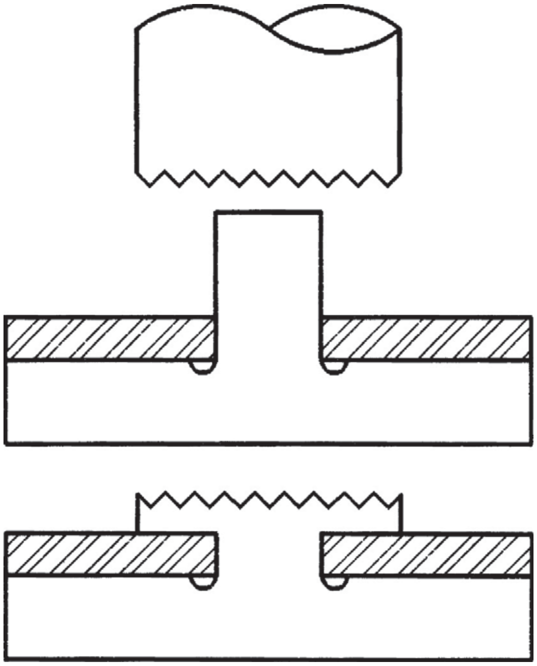


Figure 18.37. Knurled ultrasonic stake (Source: Branson Ultrasonics Corp.).

cavity, and multiple stakes may be made without concern for precise alignment or stud diameter.

Flush staking (Fig. 18.38) is used when a raised stud head is not permitted above the surface of the attached part, and the attached part has sufficient thickness to allow for a recess. The flush stake uses the tapered stud design used for dome staking, a flat-faced horn, and a countersunk hole in the attached part to contain the melt [34].

A hollow stake (Fig. 18.39) is used with studs greater than or equal to 4.8 mm (0.19 inches). Hollow studs prevent surface sinks and internal voids in molding. Staking a hollow stud produces a strong head without having to melt a large volume of material. It is useful when disassembly for repair is necessary. Repairs can be made by removing the formed stud head for access to internal components, and driving a self-tapping screw into the inside diameter for reassembly [34].

In designs for any of the staking configurations, incorporating a radius at the base of the stud helps in eliminating areas of high stress concentration, which may produce burning or fracturing of the stud at the base. Part-to-part fit of the stud and the hole is critical. A gap between the stud diameter and hole diameter could allow material to flow into the gap, making less material available to form the head. The fit should be as close as possible, or excess material should be added to compensate for the loss.

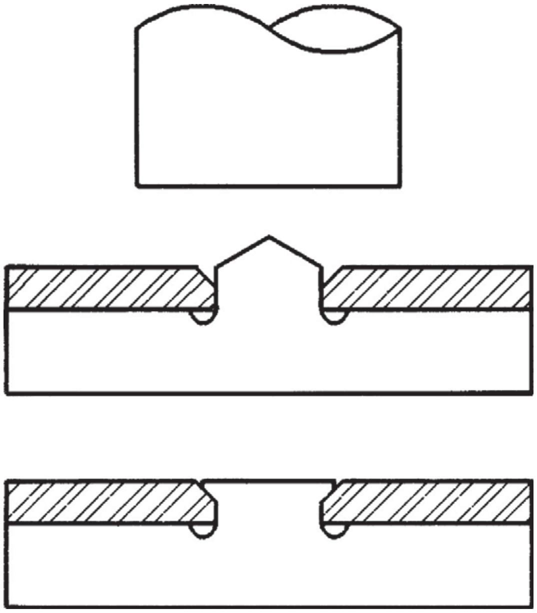


Figure 18.38. Flush ultrasonic stake (Source: Branson Ultrasonics Corp.).

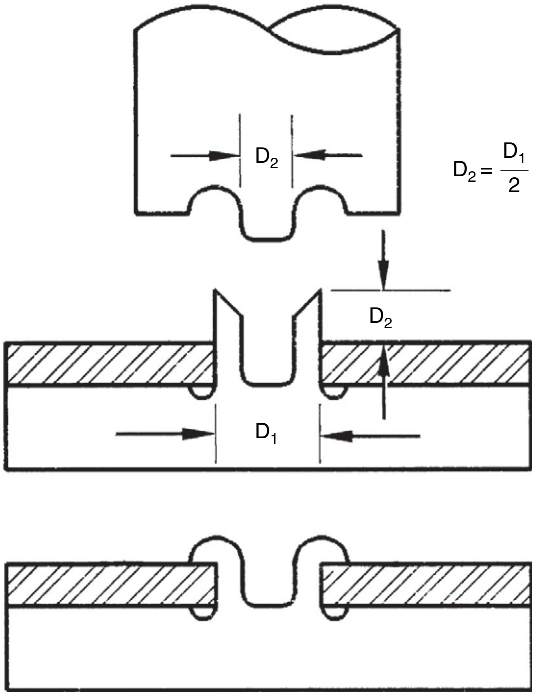


Figure 18.39. Hollow ultrasonic stake (Source: Branson Ultrasonics Corp.).

An alternative ultrasonic staking method, called high pressure or cold forming, can also be used for resilient materials such as IPS, PE, PP, and ABS. In this method, the top of the stud is reformed without reaching its melting temperature. Polycarbonate and acetal have also been found to work well with this method [34].

18.8.7 IR Staking

IR staking is similar to ultrasonic and hot-air staking, but produces a smaller HAZ, and does not produce any part marking.

IR staking usually works in two modes: single movement or dual movement modes. In the case of the former, IR is transmitted through a special glass lens that acts as the top of the cavity, which defines the final shape of the stake. However, since the lens is typically made from glass or quartz and is in direct contact with molten plastic, this mode is not recommended for filled plastics due to excessive tool wear. For filled materials, a dual process movement is recommended. Here the forming tool and the IR source are designed into separate components requiring two movements during the process, which increases cycle time (Table 18.3).

18.9 Swaging

In swaging, a ridge in one part is formed, using a tool to entrap another part, without forming a molecular bond. The forming can be performed using either a heated tool or ultrasonics (Fig. 18.40).

Ultrasonic swaging is faster than using a heated tool. Pretriggering is used so that the vibrating horn immediately begins melting the material as soon as it contacts the ridge.

The main advantage of swaging is that molds are much simpler and therefore cheaper than those requiring undercuts or studs.

Table 18.3. Typical IR Staking Cycle Times

Step	Typical IR staking times (s)	
	Single Movement Process	Dual Movement Process
Loading parts	3–10	3–10
Press actuation	1–2	1–2
IR radiation application	3–15	3–15
Application of forming tools	–	1–3
Hold phase	1–3	1–3
Part unloading	5–10	5–10

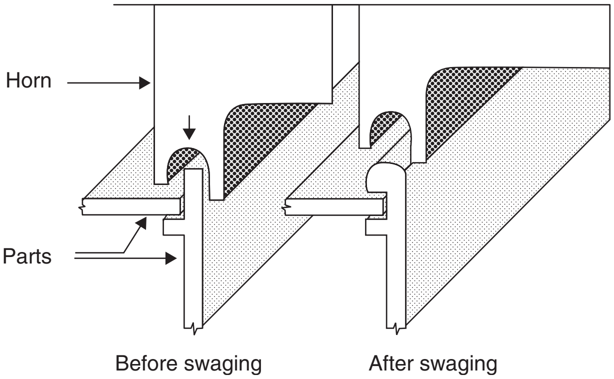


Figure 18.40. Principle of ultrasonic swaging.

The most suitable plastics for ultrasonic swaging are those with low-to-medium stiffness, such as ABS, IPS, PE, PMP, and PP. However, the technique can also be used on stiffer materials, albeit with greater difficulty.

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19 Acetal

19.1 General

Hoechst Celanese: Celcon

Molded parts of Celcon acetal copolymer are readily joined by a variety of techniques. The crystalline polymer permits a high degree of long-term structural loading on the joined assembly up to maximum service temperatures of 104°C (220°F) in air and 82°C (180°F) in water. However, care must be taken to ensure that assembly designs do not damage the surface of the male or female molded part, which could reduce the mechanical properties such as impact strength.

Reference: *Designing with Celcon Acetal Copolymer*, Supplier design guide (95-303/5M/1295), Hoechst Celanese, 1995.

BASF AG: Ultraform

Ultraform parts can be welded by heating-element (thermal contact and radiation) methods, and also by ultrasonic, vibration, and spin welding methods. However, high frequency welding is not feasible, for Ultraform on account of the low dielectric dissipation factor.

The laser irradiation welding method is suitable for joining parts molded from Ultraform, which is transparent to IR radiation (e.g., natural-colored), to parts molded from grades of Ultraform that absorb IR radiation (e.g., containing carbon black). Thus, very clean welded joints can be produced without flash.

Ultrasonic welding is preferred in cases where short welding times and ready integration into fully automated production lines are required. The strongest welded joints are achieved with the heating-element method.

Reference: *Ultraform in Processing*, Supplier design guide, BASF Aktiengesellschaft.

19.2 Heated Tool Welding

Ticona: Hostaform

Hot plate welding has proved a successful method of joining Hostaform injection molded components, irrespective of pigment or additive content. This method is particularly suitable for joints that are to be mechanically stressed, for large joints, or for components whose particular shape precludes the use of other methods.

The hot plate temperature should be between 220°C (428°F) and 240°C (464°F). The heating up time is about 5–30 seconds, depending on the shape of the component and the melt viscosity of the particular Hostaform component being used.

Reference: *Hostaform Acetal Copolymer (POM)*, Supplier design guide, Ticona, 2000.

Cadillac Plastic and Chemical Company: Cadco

Cadco acetal parts can be joined to achieve strong, permanent, leak-free, and pressure-tight joints by rapid fusion-type welding. To accomplish the weld, the joint surfaces of the parts are held lightly against a hot metal surface. The surface temperature is 288°C (550°F) and the contact time is 2–20 seconds, depending on joint geometry. When surface melting occurs, the heating tool is removed and the surfaces to be welded are quickly brought together and held under light pressure. This procedure can be used for welds up to 12.7 mm (0.5 inches) wide. Wider joints should be sheared across each other during the contacting movement to prevent air entrapment, and to ensure good weld strength.

In general, lap-joints are preferred over butt joints. A small uniform bead of flash around the joint indicates that the weld quality is good. When necessary, flash can be avoided by using an open flange on the joint perimeter to accommodate melted material expelled from the joint. Flash can also be trimmed by mechanical means. A heating tool made of aluminum will be light, corrosion resistant, and possess a high thermal conductivity. Tool surfaces should be coated with a layer of Teflon nonstick finish to prevent stringing and sticking of molten resin.

Reference: *Cadco Engineering Plastics*, Supplier design guide (CP-200-92), Cadillac Plastic and Chemical Company, 1992.

19.3 Ultrasonic Welding

DuPont: Delrin

Delrin 500 parts weld easier than parts of the higher melt viscosity Delrin 100. The difference is very slight with the shear joint but more pronounced with the butt type joints. Delrin 570, a glass-filled composition, may also be ultrasonically welded. Atmospheric moisture does not appear to influence the welding of parts of Delrin.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I*, Supplier design guide, DuPont Company, 2002.

Hoechst Celanese: Celcon

In ultrasonic welding, electrical energy is converted into vibrational energy of approximately 20 kHz (most widely used) or 40 kHz (used for small, delicate parts). The energy is then amplified and transmitted to the mating part in contact with the machine. The vibrating part rubs against the stationary second part and quickly melts the surface by frictional heat. Bonding is virtually instantaneous, and the bond strength is close to 100% of the tensile strength of Celcon acetal, especially when a shear joint is used. With this type of joint, welding is accomplished by melting the small initial contact area and then continuing the melting process with a controlled interface along the vertical walls as the parts telescope together. Interference guidelines are given in Table 19.1. This process creates a strong, structural seal as the molten interface completely fills the empty spaces between the two mating parts.

Once the proper operating conditions have been established, virtually any grade of Celcon acetal can be ultrasonically welded. Glass-reinforced grades, however, will only possess the bonding strength of the unreinforced grades since the glass does not extend through the mating surface of the two parts. "Bowing" (distortion) of flat, circular parts sometimes occurs during ultrasonic welding. This can usually be eliminated by increasing wall thickness and/or adding internal support ribs. Minimizing the weld time is also helpful.

Design and quality control of the parts, proper placement of the welding amplifier ("horn") and maintenance of equipment settings are all critical to obtaining consistent and reproducible adhesion. It should also be pointed out that the method is most successful for joining parts with similar or equivalent melting characteristics and chemical compatibility, that is, Celcon acetal copolymer to itself.

Reference: *Designing with Celcon Acetal Copolymer*, Supplier design guide (95-303/5M/1295), Hoechst Celanese, 1995.

Cadillac Plastic and Chemical Company: Cadco

Parts made from Cadco acetal can be successfully welded using conventional ultrasonic welding equipment. A vibration frequency of about 20,000 cycles per second is transmitted to the part surfaces to be joined, by means of a special tool called a horn. The vibrations cause a thin film of material to melt at the joint surface. Solidification and a subsequent weld occur under pressure after the vibrations stop.

Reference: *Cadco Engineering Plastics*, Supplier design guide (CP-200-92), Cadillac Plastic and Chemical Company, 1992.

DuPont: Delrin

Lubricants and pigments negatively influence welding. With welding equipment set at conditions that produce quality welds in unpigmented parts, the quality of welds in pigmented parts may be markedly lower—reflected in welds of lower strength and greater brittleness. The presence of pigments appears to influence the means of heat generation at the joint. Often, lower weld quality may be offset by welding pigmented parts for longer weld times than for unpigmented parts. However, these longer weld times may produce undesirable effects such as the formation of excess weld flash and marring under the welding horn. Use of dye

Table 19.1. Interference Guidelines for Shear Joints Used in Ultrasonic Welding of Celcon Acetal

Maximum Part Dimension mm (inches)	Interference per Side mm (inches)	Part Dimension Tolerance mm (inches)
<18 (0.75)	0.2–0.3 (0.008–0.012)	±0.025 (0.001)
18–35 (0.75–1.5)	0.3–0.4 (0.012–0.016)	±0.050 (0.002)
>35 (1.5)	0.4–0.5 (0.016–0.020)	±0.075 (0.003)

coloring systems, which do not significantly affect ultrasonic welding, may offer an alternative solution.

The adverse effects on ultrasonic weldability caused by pigments also apply to the welding of materials with externally or internally compounded lubricants and mold release agents. Relatively small quantities of such materials appear to affect adversely the means of heat generation in the joint during welding. If spray-on mold release agents are used in the molding of otherwise unlubricated molding material, these parts should be thoroughly cleaned prior to welding.

Reference: *Ultrasonic Welding of Delrin Acetal Resin, Zytel Nylon Resin, Lucite Acrylic Resin,* Supplier technical report (171), DuPont Company, 1972.

19.4 Vibration Welding

DuPont: Delrin

All grades of Delrin are suitable for vibration welding. Delrin 500F gives the best results, whereas Delrin 100 is somewhat inferior. Weld joints on parts in Delrin 100 are usually the weakest area due to the high elongation of this resin. The same part molded in Delrin glass filled resin does not break at the joint but at a corner, because of the lower elongation. It must also be kept in mind that colored compositions have lower weld strength than the same grade in natural color.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I*, Supplier design guide, DuPont Company, 2002.

19.5 Spin Welding

DuPont: Delrin

As a first approximation, the peripheral welding speed for Delrin should be chosen between 3 and 5 m/s (10–16 ft/s). Then the pressure must be adjusted until the desired result is obtained in a welding time of 2–3 seconds.

With plastics such as acetal resins that have a narrow melting temperature range, the tool should not perform more than one or two revolutions once contact has been made. If the pressure between the two parts is too low, the flyweight will spin too long, and material will be sheared off as the plastic solidifies, producing welds that are weak, or that will leak.

Once the material has melted, it will take some time to resolidify, so it is vital to keep up the pressure for a certain period of time, which will depend on the particular plastic, and is best determined experimentally. For Delrin, this is about 0.5–1 second.

The appearance of the flash depends not only on the type of plastic, but also on its viscosity and on any fillers. For example, Delrin 100 produces a rather fibrous melt, while Delrin 500 gives a molten weld flash.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I,* Supplier design guide, DuPont Company, 2002.

Ticona: Hostaform

Experience has shown that frictional speeds of 100–300 m/minute (5.5–16.5 ft/s) at constant pressures of 0.2–0.5 N/mm^2 (29–73 psi) give successful results.

Reference: *Hostaform Acetal Copolymer (POM)*, Supplier design guide, Ticona, 2000.

Cadillac Plastic and Chemical Company: Cadco

When properly performed, spin welding quickly produces strong, permanent, and leak-free welds. Spin welds are made by rotating the part surfaces to be welded at high speeds relative to each other. When a film of melted acetal is formed, relative motion is stopped, and the weld is allowed to solidify under pressure. The spin welding operation can be performed in 1–2 seconds while production assembly rates for small parts may be as high as 60 pieces per minute through the use of automatic part handling equipment.

Reference: *Cadco Engineering Plastics*, Supplier design guide (CP-200-92), Cadillac Plastic and Chemical Company, 1992.

19.6 Hot Gas Welding

Cadillac Plastic and Chemical Company: Cadco

Heavy sections of Cadco acetal can be joined by hot gas welding. A hot nitrogen welding gun, pressure regulator, filler rods of acetal and appropriate jigs and fixtures are needed for this technique. Use of a nitrogen “blanket” is recommended to avoid oxidation leading to low weld strength. The outlet temperature of the welding gun should be approximately 332°C (630°F). For maximum joint strength, both the parts to be welded, and the filler rod should be heated so that all surfaces to be joined are melted.

Reference: *Cadco Engineering Plastics*, Supplier design guide (CP-200-92), Cadillac Plastic and Chemical Company, 1992.

19.7 Laser Welding

Acetal

This section reviews the results of welding experiments using a box geometry with a three-dimensional weld line. The laser source was a diode laser with a wavelength of 940 nm. The focus dimensions of the laser beam were 1.5 × 1.5 mm (0.059 × 0.059 inches). The laser head was fixed to an extension arm of a 6-axis robot. An analysis of the welding process was completed using a standardized design of experiments. The parameters studied were laser power, velocity of the laser, and welding pressure. The lower, absorbing layer contained <0.1 wt.% carbon black.

With a laser velocity of 20 mm/s (0.8 inches/s), welding times of 12 seconds could be achieved. Low energy densities (1.5 J/mm^2) resulted in the lowest burst pressure. Increasing energy density increased the burst pressure to a maximum (at an energy density of 3.25 J/mm^2). At higher energy densities, the burst pressure declined again. It is inferred that once a laser density becomes too large, decomposition products appear, affecting the weld quality.

Reference: Haberstroh E, Luetzeler R: 3-D laser transmission welding. ANTEC 2003, Conference proceedings, Society of Plastics Engineers, Nashville, May 2003.

BASF: Ultraform

Suitable Ultraform combinations for laser welding are given in Table 19.2.

Reference: *Transmission Laser-Welding of Thermoplastics*, Technical Information (WIS 0003 e 01.2001), BASF Aktiengesellschaft, 2001.

Table 19.2. Ultraform Product Combinations Suitable for Laser Welding

Transmitting Component	Absorbing Component
N2320 003	W2320 003 sw 11020 oder sw 120
S2320 003	W2320 003 sw 11020 oder sw 120
W2320 003	W2320 003 sw 11020 oder sw 120

19.8 Solvent Welding

DuPont: Delrin

Delrin parts can be joined together using solvent welding with hexafluoroisopropanol. No surface roughening is needed, and the bonded joint is stronger than that achieved with standard adhesives.

Reference: *Delrin Design Information*, Supplier design guide (L-10464), DuPont, 2003.

Ticona: Hostaform

Hexafluoroacetone sesquihydrate can be used for solvent bonding Hostaform. The bond strengths obtainable with this solvent are better than those that can be achieved with conventional adhesive systems. Hostaform moldings bonded with hexafluoroacetone sesquihydrate have withstood shear stresses up to 10 MPa (1450 psi).

It should be noted that hexafluoroacetone sesquihydrate is toxic. It gives off vapors that irritate the respiratory tract, and should therefore only be handled under extraction hoods.

Reference: *Hostaform Acetal Copolymer (POM)*, Supplier design guide, Ticona, 2000.

Cadillac Plastic and Chemical Company: Cadco

Cadco BA-410 cement is suitable for joining Cadco acetal stock shapes.

Reference: *Cadco Acetal*, Supplier technical report, Cadillac Plastic and Chemical Company.

19.9 Adhesive Bonding

DuPont: Delrin 100

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol.

The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm), and a traverse speed of 0.01 inches/s (0.25 mm/s).

While the bond strengths in Table 19.3 give a good indication of the typical bond strengths that can be achieved as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 19.3, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real-world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Table 19.3. Shear Strengths of Delrin 100 Acetal to Acetal Adhesive Bonds Made Using Adhesives Available from Loctite Corporation*

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled Resin	30 rms	100 (0.7)	200 (1.4)	1700 (11.7)	500 (3.5)	50 (0.3)	250 (1.7)
Roughened	47 rms	150 (1.0)	600 (4.1)	1700 (11.7)	500 (3.5)	100 (0.7)	250 (1.7)
Antioxidant	0.2% Irganox 1010	100 (0.7)	400 (2.8)	1700 (11.7)	500 (3.5)	50 (0.3)	250 (1.7)
UV stabilizer	0.2% Tinuvin 328 0.4% Tinuvin 770	100 (0.7)	900 (6.2)	1700 (11.7)	500 (3.5)	50 (0.3)	300 (2.1)
Impact modifier	30% Estane 5708F1	100 (0.7)	350 (2.4)	1700 (11.7)	500 (3.5)	50 (0.3)	350 (2.4)
Lubricant	3.88% N,N'-Ethylene bisstearamide wax	100 (0.7)	350 (2.4)	1700 (11.7)	900 (6.2)	50 (0.3)	450 (3.1)
Glass filler	20% type 3090 glass fiber	100 (0.7)	1100 (7.6)	2800 (19.3)	1100 (7.6)	50 (0.3)	300 (2.1)
PTFE filler	15% PTFE MP1300	100 (0.7)	200 (1.4)	1700 (11.7)	100 (0.7)	50 (0.3)	250 (1.7)
Colorant	4% 3972 colorant	100 (0.7)	200 (1.4)	1700 (11.7)	500 (3.5)	50 (0.3)	250 (1.7)
Antistatic	1.5% Markstat AL12	150 (1.0)	1750 (12.1)	1700 (11.7)	1100 (7.6)	50 (0.3)	250 (1.7)
Acetal copolymer	Celcon courtesy of Hoechst Celanese	50 (0.3)	100 (0.7)	300 (2.1)	100 (0.7)	200 (1.4)	200 (1.4)

*All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive performance: Prism 401 instant adhesive, when used in conjunction with Prism Primer 770, achieved the highest bond strengths on all of the acetal formulations that were evaluated. Hysol E-214HP epoxy adhesive, Hysol 3631 hot melt adhesive, Hysol U-05FL urethane adhesive, Super Bonder 414 instant adhesive, and Loctite 3030 adhesive achieved the second highest bond strengths. Depend 330 and 5900 flange sealant achieved the lowest bond strengths on acetal polymers. The addition of an antistatic additive to acetal homopolymer resulted in a large, statistically significant increase in the bond strengths achieved when using Prism 401, Prism 4011, or Super Bonder 414 instant adhesives.

Surface treatments: Surface roughening either caused no effect, or a statistically significant increase in bond strength achieved on acetal homopolymer. The use of Prism Primer 770 in conjunction with Prism 401 instant adhesive caused a statistically significant increase in the bondability of both acetal homopolymer and copolymer.

Other information: The surface of acetals tends to be very dry, so an accelerator may be necessary to speed up the cure of cyanoacrylates. Acetal homopolymers are compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol, and Loctite ODC Free Cleaner and Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

Ticona: Hostaform

Because of its high solvent resistance, Hostaform does not readily bond with conventional adhesives. Joints made with pressure-sensitive adhesives are the only type possible. To obtain high-strength bonds, the surfaces must be pretreated. Suitable options include mordant solutions, primer coats, or corona discharge.

After thorough surface pretreatment, the following adhesive systems can be used:

- Contact adhesives: polychlorobutadiene with isocyanate cross-linking agents
- Two-component adhesives: epoxy resin, polyurethane, nitrile rubber/phenolic resin, methacrylate
- Hot-melt adhesives: vinyl copolymers
- One-component polymerizable adhesive: cyanoacrylate

Reference: *Hostaform Acetal Copolymer (POM)*, Supplier design guide, Ticona, 2000.

Acetal

Acetal can be bonded using anaerobic and cyanoacrylate adhesives. Abrasion can help. If bonding with cyanoacrylate adhesive, use Permabond POP primer.

Reference: *The Engineers Guide to Adhesives*, Supplier design guide, Permabond Engineering Adhesives.

Cadillac Plastic and Chemical Company: Cadco

The nonstick and/or solvent resistant nature of Cadco acetal requires that part surfaces be specially prepared before adhesive bonding can occur. The surfaces can then adhere to like substrates or others such as wood, steel, and aluminum.

Roughing techniques such as “satinizing” and sanding with a 280A grit emery cloth have been successful with Cadco acetal surfaces. “Satinizing” is a chemical etching process developed by DuPont for Delrin acetal. In the process, a mildly acidic solution produces uniform anchor points on the surface.

Reference: *Cadco Engineering Plastics*, Supplier design guide (CP-200-92), Cadillac Plastic and Chemical Company, 1992.

DuPont: Delrin 100

The adhesive joining of Delrin acetal resin is generally limited to prototype models with low shear forces. This is because the shear strength achieved with most adhesives is only 2%–10% of the available shear strength of Delrin acetal resin. The best adhesion requires a special roughening step such as “satinizing” or sanding with 280 grit emery cloth. The satinizing technique gives the best joints.

Reference: *Delrin Design Handbook for Du Pont Engineering Plastics*, Supplier design guide (E-62619), Du Pont Company, 1987.

BASF AG: Ultraform

In order to activate this nonpolar material, it is necessary to pretreat the surfaces, for example, by etching, priming, or corona discharge. Adhesive bonding is possible only with pressure-sensitive adhesives. The joint obtained is impervious to gas, air, and moisture, but has only low mechanical strength.

Reference: *Ultraform in Processing*, Supplier design guide, BASF Aktiengesellschaft.

19.10 Mechanical Fastening

DuPont: Delrin

Self-tapping screws: Tables 19.4 and 19.5 give the numerical values of the pull-out strengths, stripping torque, and dimensions for Type AB screws of various sizes.

Snap-fits: The suggested allowable strains for lug type snap-fits are given in Table 19.6.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I*, Supplier design guide, DuPont Company, 2002.

Ticona: Hostaform

Riveting: To join Hostaform components with each other or with parts made from other materials, hot riveting and ultrasonic riveting are suitable methods. In hot riveting, a PTFE-coated tool is brought up to a temperature of about 220–230°C (430–450°F). In the first stage, the rivet is preheated with the tool and in the subsequent stage, the head is formed with a cold heading tool.

Reference: *Hostaform Acetal Copolymer (POM)*, Supplier design guide, Ticona, 2000.

Hoechst Celanese: Celcon

Snap-fit assemblies: The maximum permissible elongation for most Celcon acetal grades used for barbed leg snap-fits is 6%, and for cylindrical or ball and socket snap-fits it is 4%.

Another type of snap-fit assembly is called a snap-on or snap-in fit. It can sometimes be molded into the part, and is most often used with rounded parts. Its advantage is that in operation, some or all of the entire part flexes, but the total deflection is very small and is

Table 19.4. Pull-out Load Performances for Various Screw Dimensions in Delrin Resins

		Screw No.	6	7	8	10	12	14
		D_s, mm	3.6	4.0	4.3	4.9	5.6	6.5
		d_s, mm	2.6	2.9	3.1	3.4	4.1	4.7
		D_h, mm	8.9	10.0	10.8	12.2	14.0	16.2
		d_h, mm	2.9	3.3	3.5	4.1	4.7	5.5
Pull-out force	Delrin 500 NC010	N	3100	3800	4500	5250	6500	9000
	Delrin 570	N	3050	3600	4250	4950	6000	8300

D_s: major diameter of screw thread; d_s: pitch diameter of screw; D_h : boss outside diameter; d_h: boss hole diameter.

Table 19.5. Stripping Torque Performances for Various Screw Dimensions in Delrin Resins

		Screw No.	6	7	8	10	12	14
		D_s, mm	3.6	4.0	4.3	4.9	5.6	6.5
		d_s, mm	2.6	2.9	3.1	3.4	4.1	4.7
		D_h, mm	8.9	10.0	10.8	12.2	14.0	16.2
		d_h, mm	2.9	3.3	3.5	4.1	4.7	5.5
Stripping Torque	Delrin 500 NC010	Nm	2.5	3.5	4.6	5.8	7.5	11.2
	Delrin 570	Nm	2.5	3.5	4.7	6.2	8.2	12.0

D_s: major diameter of screw thread; d_s: pitch diameter of screw; D_h : boss outside diameter; d_h: boss hole diameter.

Table 19.6. Suggested Allowable Strains for Lug-Type Snap-fits in Delrin Resins

Material	Allowable strain (%)	
	Used once (new material)	Used frequently
Delrin 100	8	2–4
Delrin 500	6	2–3

well below the yield strain value. Snap-ons are also amenable to release of the assembled part by using a tool to provide a releasing force. This is required when it may be necessary to have repeated servicing of the operating equipment within the plastic assembly.

Tapping and self-tapping screws: Both thread-cutting and thread-forming screw designs are widely used. Combinations of both designs are very popular because they have excellent holding power, and they minimize stresses produced during thread forming. Some guidelines for self-tapping screws are:

- Size the diameter of the pilot hole properly to minimize hoop stress from undersized holes. Pilot hole tolerances of ±0.025 mm (0.001 inches) give optimum fastening strengths.
- Control the depth of the molded or drilled hole to prevent bottoming of the leading edge of the screw.
- If a boss is used to anchor the screw, the outside diameter of the boss should be at least twice the major diameter of the screw.
- Do not use thread-forming screw designs on glass-reinforced plastics such as Grade GC-25A.
- Use torque-controlled drivers on production lines to avoid stripping or high-stress assemblies.

Molded-in threads: Mating male and female threads molded into the parts to be assembled characterize this type of assembly. It is not widely used for parts of Celcon acetal because its chief applications are containers, caps, and molded plastic hardware.

Reference: *Designing with Celcon Acetal Copolymer*, Supplier design guide (95-303/5M/1295), Hoechst Celanese, 1995.

Cadillac Plastic and Chemical Company: Cadco

Snap-fit assemblies: Snap-fitting is a quick, simple, and economical method of assembling Cadco acetal parts to other plastic materials or metals. In general, a machined undercut on one part engages a mating lip on the other to retain the assembly. Although a snap-fit is strong, it is usually not pressure tight unless other features such as O-rings are incorporated in the joint design.

Press-fit assemblies: Press-fitting Cadco acetal parts to other plastics or metals provides joints of high strength at minimum cost. In general, suggested interferences are larger between parts of Cadco acetal than between metal parts since the elastic modulus of acetal is lower than that of metals. Use of large rather than small interferences can result in production economy because of greater latitude with production tolerances.

Staking: Heading (staking) is useful in forming low cost, strong, and permanent mechanical joints between Cadco acetal parts, or between Cadco acetal and other materials. Heading involves permanent deformation of a rivet, stud or similar part. Cold heading is accomplished by compressing the end of a rivet while holding and containing the rivet body at room temperature. When the compressive load exceeds acetal's yield point, the rivet end is formed into a head. Less heading force is required when hot heading. Heading at the maximum suggested temperature of 149°C (300°F) results in minimum recovery of the head (with low heading force).

Tapping and self-tapping screws: Using self-tapping screws to join Cadco acetal parts may provide substantial cost savings by simplifying machined parts and reducing assembly costs. A self-tapping screw cuts or forms thread as it is inserted so a separate tapping operation is not required.

Reference: *Cadco Engineering Plastics*, Supplier design guide (CP-200-92), Cadillac Plastic and Chemical Company, 1992.

BASF AG: Ultraform

The mechanical properties of Ultraform, especially its toughness, allow the use of self-tapping screws. Ultraform parts can be connected without difficulty to one another, or to parts made from other materials by means of rivets and bolts. Snap-in and press-fit connections can also withstand high stresses. Ultraform's outstanding elasticity and strength, even at high temperatures, are particularly suitable for this form of construction.

Reference: *Ultraform in Processing*, Supplier design guide, BASF Aktiengesellschaft.

20 Acrylic Resin

20.1 General

Altuglass International: Plexiglas

Plexiglas acrylic resins may be welded to other thermoplastics (Table 20.1).

Reference: *Plexiglas Technical Data. Welding Methods*, Supplier technical data sheet, Altuglass International, 2006.

20.2 Heated Tool Welding

Altuglass International: Plexiglas

The following hot plate welding parameters may be used as a reference point when welding Plexiglas resins:

- Temperature: 600–800°F (315–425°C)
- Melt-depth: 0.03–0.04 inches (0.76–1.00 mm)
- Seal depth: 0.01–0.02 inches (0.25–0.51 mm)

Reference: *Plexiglas Technical Data. Welding Methods*, Supplier technical data sheet, Altuglass International, 2006.

Acrylic [form: 3 mm (0.118 inch) thick sheet]

With increasing melt layer thickness, hence an increasing hot plate temperature and/or heating time, there was an increase in the component's susceptibility to stress cracking. As far as process control is concerned, this means the lowest possible heating time and hot plate temperature should be selected. This is not, however, in the interests of the cost efficiency of the process, and the additional costs incurred through increased cycle time must be set against the costs of heated component storage subsequent to the welding process.

Reference: Potente H, Schnieders J: Influence of process parameters on the phenomenon of stress cracking during hot plate welding. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

20.3 Ultrasonic Welding

Altuglass International: Plexiglas

The following welding parameters may be used as a reference point when ultrasonic welding Plexiglas resins at 20 kHz frequency:

- Amplitude: 40–70 µm
- Pressure: 30–60 psig (0.2–0.4 MPa)

Reference: *Plexiglas Technical Data. Welding Methods*, Supplier technical data sheet, Altuglass International, 2006.

Rohm and Haas: Plexiglas

Parts molded from Plexiglas acrylic resins can be assembled by ultrasonic welding, provided they are properly designed and molded using conditions that minimize stress.

Reference: *Plexiglas Acrylic Resin from AtoHaas Clearly the Best*, Supplier marketing literature (PL-1700b), Atohaas, 1993.

Table 20.1. Guideline for Welding Plexiglas to Other Thermoplastics

	Plexiglas V-Series			Plexiglas MI-7			Plexiglas DR		
	Ultrasonic	Vibration	Hot Plate	Ultrasonic	Vibration	Hot Plate	Ultrasonic	Vibration	Hot Plate
PMMA	G	E	E	G	E	E	G	E	E
ABS	G	E	E	G	E	E	G	E	E
ABS/PC	G	VG	VG	G	VG	VG	G	VG	VG
PC	G	VG	VG	G	VG	VG	G	VG	VG

E: excellent (weld strength 90–100% of tensile strength of weaker material); VG: very good (weld strength 70–90% of tensile strength of weaker material); G: good (weld strength 50–70% of tensile strength of weaker material).

DuPont: Lucite

Because Lucite acrylic is an amorphous resin, parts made of this material may be welded with greater ease than parts of semicrystalline plastics. Differences in weldability of natural compositions in the various flow grades of Lucite 129, 130, 140, 147, and 148 have not been detectable in actual applications.

Welded joints between parts of Lucite may be transparent if the joint is properly designed. Weld flash is translucent and must be trimmed mechanically. It is practically impossible to obtain an optically transparent joint without weld flash at the extremities of the weld. If welding conditions are adjusted to eliminate flash, an optical discontinuity will remain.

Atmospheric moisture does not appear to influence ultrasonic welding of Lucite. Pigments, lubricants, and mold release agents may negatively influence welding. With welding equipment set at conditions that produce quality welds in unpigmented parts, the quality of welds in pigmented parts may be markedly lower—reflected in welds of lower strength and greater brittleness.

The presence of pigments appears to influence the means of heat generation at the joint. Often, lower weld quality may be offset by welding pigmented parts for longer weld times than for unpigmented parts. However, these longer weld times may produce undesirable effects such as the formation of excess weld flash and marring under the welding horn. Use of dye coloring systems, which do not significantly affect ultrasonic welding, may offer an alternative solution.

The adverse effects on ultrasonic weldability caused by pigments also apply to the welding of materials with externally or internally compounded lubricants and mold release agents. Relatively small quantities of such materials appear to affect adversely the means of heat generation in the joint during welding. If spray-on mold release agents are used in the molding of otherwise unlubricated molding material, these parts should be thoroughly cleaned prior to welding.

Reference: *Ultrasonic Welding of Delrin Acetal Resin, Zytel Nylon Resin, Lucite Acrylic Resin,* Supplier technical report (171), DuPont Company, 1972.

Acrylic (form: fiber)

Acrylics can be ultrasonically tacked or cut. Continuous bonding is generally unsatisfactory due to embrittlement and low strength.

Reference: *Ultrasonic Sealing and Slitting of Synthetic Fabrics*, Supplier technical report, Sonic & Materials, Inc.

20.4 Vibration Welding

Altuglass International: Plexiglas

The following welding parameters may be used as a reference point when vibration welding Plexiglas resins:

- Amplitude: 0.03–0.07 inches (0.76–1.78 mm)
- Pressure: 200–500 psig (1.4–3.4 MPa)

Reference: *Plexiglas Technical Data. Welding Methods*, Supplier technical data sheet, Altuglass International, 2006.

20.5 Laser Welding

Acrylic [form: 3 mm (0.118 inch) thick plates]

Welding trials were carried out using a Nd:YAG laser operating at a wavelength of 1064 nm. A thin film of methylmethacrylate (MMA) containing a near infrared absorber dye was placed at the interface of the pieces to be welded. The dye concentration was approximately 0.02% in weight, and the film thickness was 12 μm. The film strip width was 5 mm (0.2 inches) and the laser beam was circular with a diameter of approximately 6 mm (0.24 inches). It was positioned to heat the full width of the film. The laser power used was 100 W at a welding speed of 8 mm/s (0.315 inches/s).

Welded samples were tensile-tested and failure was observed, not across the weld interface but in the parent material near the edge of the weld. The failure force was 50 N/mm weld-width.

Reference: Jones IA, Taylor NS, Sallavanti R, Griffiths J: Use of infrared dyes for transmission laser welding of plastics. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

Acrylic

Investigations were conducted with a Holmium-YAG laser, which emits radiation at a wavelength of 2.1 μm. A welding operation based on volume absorption of the laser energy is possible using this type of laser with PMMA.

Both parts, which were joined in a butt joint configuration, melted over the entire cross-section, for a laser power of 20 W and a welding speed of 300 mm/minute (11.8 inches/minute).

Reference: Herfurth H, Ehlers B, Heinemann S, Haensch D: New approaches in plastic welding with diode lasers. Laser Materials Processing, ICALEO '99, Conference proceedings, San Diego, November 1999.

20.6 Infrared Welding

Acrylic

Through-transmission infrared welding (TTIR) involves transmission of radiant energy through a nonabsorbing polymer, such as acrylic. The energy is absorbed by an absorbing polymer that is in contact with the acrylic, such as black polycarbonate. Contact is maintained during the welding process by the application of a weld force. Absorption of the energy heats the absorbing polymer and, through the direct contact, the nonabsorbing one. As both melt, the weld force causes the chains to mix and create the weld.

Through-transmission infrared welding offers a promising way to join materials together in a continuous (as well as static) process where access to only one side of the weld zone is needed. For welding of PMMA to PC, this work demonstrates that strong welds with good aesthetics were possible. While the process inherently provides selective heating of the plastic parts, this work describes ways to further enhance this selectivity in a dramatic way.

Reference: Grimm RA: Through-transmission infrared welding of polymers. ANTEC 1996, Conference proceedings, Society of Plastics Engineers, Indianapolis, May 1996.

20.7 Microwave Welding

Acrylic

Microwave welding was carried out using a single-mode cavity, connected to a 2.45 GHz microwave generator with 1000 W maximum power. The polymer used was PMMA with dimensions of 100 × 25 × 2 mm (3.94 × 0.98 × 0.08 inches). The microwave implant material was Ormecon L5006 polyaniline. Since this was in liquid form, it was necessary to make channels in order to pattern it. These were fabricated using a CNC micro-milling machine to different widths (0.4, 0.6, 0.8, and 1.0 mm; 0.016, 0.024, 0.031, and 0.039 inches) and a constant depth of 0.3 mm (0.012 inches) and a length of 12 mm (0.47 inches).

It was found that increasing the amount of polyaniline increased the joint strength with an increasing microwave power. A power of 300 W provided faster heating and better bonding, and hence resulted in higher joint strength than lower powers. It was noted that at 15 seconds, the joint strength reached 6.8 MPa (986 psi) with a 0.6 mm (0.024 inch) channel of polyaniline.

Reference: Yussuf AA, Sbarski I, Hayes JP, Tran N, Solomon M: Rapid microwave welding of two polymethylmethacrylate (PMMA) substrates. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

20.8 Solvent Welding

Altuglass International: Plexiglas

Methylene dichloride has proven to be an effective solvent for bonding Plexiglas acrylic resins.

Reference: *Plexiglas Technical Data. Welding Methods. Chemical Methods*, Supplier technical data sheet, Altuglass International, 2006.

DuPont: Lucite L (features: transparent; form: cast sheet)

Methanol, ethanol, and N,N-dimethylformamide (DMF) were used to weld PMMA between 40°C (104°F) and 60°C (140°F). The solubility parameter of DMF is closest to that of PMMA, followed by ethanol and methanol. The mechanical strengths in both tear and tensile modes increased with decreasing solubility difference in the solvent and PMMA, and increasing welding temperature.

Reference: Du C-S, Hu C-T, Lee S: The microstructures of solvent-welded joints of irradiated poly(methyl methacrylate). *Journal of Adhesion Science and Technology*, 15(1), p. 83, 2001.

Cyro: Acrylite FF (form: sheet)

Acrylite FF acrylic sheet can be easily joined to itself or other acrylic surfaces with many commercially available solvents.

Preparation: The first step is preparing the area to be joined. Edges must be cleanly cut and/or properly machined. If a dull blade is used for a saw cut, resulting in a melted or chipped edge, the contact between the sawed edge and solvent may result in crazing of the material. Finish all rough edges on a joiner, shaper or edge finisher. If you cannot do so, wet-sand the edges with a flat surface or block.

Do not polish edges that are to be joined. Polishing will produce a convex edge with rounded corners and will result in an unsightly, weak joint. Also, a flame-polished edge may craze when it contacts the solvent.

Crazing may also occur if internal stresses from shop fabrication are high. To eliminate such stresses, anneal the piece at 80°C (180°F) When annealing, the heating and the cooling time in hours should each equal the material thickness in millimeters, up to 6 mm (0.24 inches). For example, you would heat a 3 mm thick sheet (0.12 inches) for three hours and allow it to cool gradually for three hours.

For thin sheet, the annealing (heating) time should not be less than two hours.

Capillary Method: Capillary solvent welding is probably the most popular way of joining Acrylite FF acrylic sheet. It works because of the ability of low-viscosity solvents to flow through a joint area by capillary action. Properly done, capillary solvent welding yields a strong, transparent joint.

For capillary welding, first make sure all parts fit together properly. Then, join the pieces together with masking tape or clamp them into a form that will support the pieces and hold them firmly in place.

When solvent welding Acrylite FF acrylic sheet, keep the joint in the horizontal plane and space the two edges with shims. Use 0.004 inch (0.1 mm) shims with sheets 1/4 inch (6.4 mm) or thinner, and 0.008 inch (0.2 mm) shims with thicker sheet. Insert shims every two feet (600 mm) for long edges.

Let the solvent soak into the edges 45–60 seconds before removing the shims. At this point, the surfaces will be soft. Apply a small pressure of about 0.7–1.4 lb/inch^2 (50–100 g/cm^2) for three minutes, until the joint is set.

If the solvent does not flow completely into the joint, tilt the vertical piece very slightly (about 1°) toward the outside. This should allow the solvent to flow freely into the entire joint. Then, tilt the piece back for a square corner.

The initial bond forms in 5–10 seconds. Wait three hours before carrying out subsequent processing. High strength is reached in 24–48 hours. Strength will continue to build for several weeks.

Dip or Soak Method: Pour a moderate amount of solvent into a dip or soak pan. Dip the edge of one of the pieces to be joined directly into the solvent. It is important that only the edge is dipped—exposing too much area to the solvent will produce a weak, slow-setting joint.

Leave the piece in the solvent for 20 seconds for thin sheet, and 30 seconds for a relatively thick material.

When you remove the sheet from the solvent, hold it for a few seconds at a slight angle to allow excess solvent to drain off. Carefully, but quickly, place the soaked edge precisely in place on the other part to be joined. Hold the parts together for about 30 seconds without applying pressure. This will allow the solvent to work on the surface of the piece that was not dipped.

After 20 seconds, apply some pressure—just enough to squeeze out the air bubbles. Do not apply too much pressure, as doing so will squeeze out the material.

When the pieces are joined, the part should be placed in a jig or clamp to maintain firm contact for 10–30 minutes. Do not allow the parts to move during this critical time.

The initial bond forms in 5–10 seconds. Subsequent processing can be carried out after three hours. The bond will achieve high strength in 24–48 hours. Strength will continue to build for several weeks.

Solvent Cementing: Use solvent cements to join parts that cannot be easily joined by the capillary or soak solvent methods—either because the joints are hard to reach, or because the edges do not fit together well. Solvent cement is thick. It will fill small gaps and make strong, transparent joints where solvents cannot do so.

Remove the masking from around the joint area and carefully apply a bead of cement to one side of the joint using a brush, spatula, or a cement applicator. Then gently join the pieces together as described in the soak method.

A solvent-resistant tape may be applied to protect the area around the joint but it should be removed carefully after about 5 minutes, while the cement is still wet. Do not touch the parts at all for the critical first 3 minutes, or the joint will not hold. The parts may be carefully moved after 10 minutes.

Some trouble shooting tips are given in Table 20.2.

Reference: *Acrylite FF Fabrication Tech Brief, Part 8 Cementing*, Supplier design guide (1319(8F)-899-5RA), CYRO Industries, 1999.

Mitsubishi Rayon: Shinkolite-A (features: transparent; form: cast sheet)

Shinkolite-A can be easily solvent welded with the following organic solvents:

Type 1: Solvent: methylenedichloride, or mixture of methylenedichloride and glacial acetic acid. Adhesion is extremely easy and adhering is very high. However, strength and outdoor durability are comparably unfavorable.

Type 2: Solvent cement: to the above solvent, a small amound of PMMA is added and dissolved.

Table 20.2. Solvent Welding of Acrylite FF—Trouble Shooting

Problem	Cause	Solution
Bubbles in joint	Uneven surface	Check joint preparation for squareness Use solvent cement
Crazing	Stresses in material	Use water cooling when sanding, etc. Anneal heat bent areas Dry before flame polishing Use proper ventilation
Whitening of joint	Water in the solvent	Replace solvent
	Fast evaporation of solvent	Reduce evaporation rate by adding glacial acetic acid (1%–3%)
Weak joints	Uneven surface	Check joint preparation for squareness Use solvent cement
	Solvent/cement problem	Check solvent storage methods Solvent evaporation can change solvent properties

Type 3: Syrup + hardening agent: to partially polymerized methyl methacrylate syrup, initiating agent for polymerization (hardening agent) is added.

The following points should be noted:

(1) Mask parts according to necessity, to avoid solvent from sticking to the parts other than the adhering area.

(2) Thoroughly wipe the adhering surface.

(3) For Type 1 welding, injection; for Type 2 cementing, oiler or eye dropper is generally used; for Type 3 cementing, make an applying opening and directly pour cement into the space. For this type, cover the upper surface with cellophane or polyester film in order to keep oxygen absorption to a minimum until polymerization is complete (oxygen absorption hinders polymerization).

(4) Defects at the time of cementing and their prevention are as follows:

   a. *Crack, craze*: Can occur when the joint is subjected to a stress from outside, when there is inner stress generated during the preprocessing stage, or when absorption is large. It is necessary to control these stresses to avoid concentration in specific areas.

   b. *Bubbles*: Occur due to bad setting of joint surfaces, evaporating rate of solvent too fast, faultly injection of solvent/cement, insufficient pressure, or polymerization too fast or partially different reactive rate. Evaporating rate can be controlled by changing the mix ratio of methylenedichloride and ethylenedichloride, and also by mixing high temperature boiling point solvent to methylenedichloride.

   c. *Haze*: When air temperature is high, parts in contact with the solvent tend to haze due to condensation of vapor which happens during evaporation of the solvent. This can be avoided by reducing the evaporation rate. Also, it is effective to add a small amount of water-soluble high temperature boiling point solvent (5%–15%) such as diacetone alcohol or glacial acetic acid.

Reference: *Shinkolite-A Technical Info-Fabrication*, Supplier technical guide, Mitsubishi Rayon.

Cyro: Cyrolite HP (features: transparent; note: proprietary formulation)

Cyrolite HP multipolymer sheet is a continuously manufactured sheet specially formulated for use with solvent welding. The methylene chloride-based solvents commonly used for acrylic sheet fabrication provide results on Cyrolite HP sheet comparable to those achieved with acrylic. This is beneficial for two reasons:

(1) Cyrolite HP sheet does not require the stocking of speciality solvent formulations.

(2) Cyrolite HP sheet can be bonded to acrylic sheet as both materials are attacked by the same solvents. This permits the use of acrylic, including extruded acrylic profiles, in conjunction with Cyrolite HP sheet in virtually any display.

Typical acrylic fabrication techniques for edge preparation and solvent application can be used with success on Cyrolite HP sheet. Finished, jointed, or clean saw cut edges are all suitable for solvent welding. Avoid using sanded or scraped edges as they may provide inconsistent surface contact along the edge. Never use a polished or buffed edge in direct contact with solvents as this will lead to crazing.

In most instances, techniques used to bond acrylic sheet can be used successfully, without modification, to bond Cyrolite HP sheet. However, due to its proprietary formulation, Cyrolite HP sheet will absorb solvent more readily than acrylic sheet. To compensate for this slight difference, fabricators must insure that enough solvent is applied to the mating edges of the pieces they are joining. The following guidelines can be used to improve results:

- Insure a smooth, clean, low stress edge.
- Apply a generous amount of solvent to the surfaces being joined. This may be enhanced by:
  - slightly tipping the vertical piece so that its edge can accept more solvent.
  - using a larger diameter applicator tip opening for more solvent flow.
  - providing space at the joint by shimming (0.002–0.004 inches; 0.05–0.1 mm).
- If weights are used, allow the solvent to attack for 1.5–2 minutes before applying them.

Joint “set-up time” is a major concern for any fabricator bonding materials on a production scale. The time required for a joint to reach sufficient strength for further processing is dependent upon a number of variables. These variables include the type of solvent used and the temperature and humidity of the welding environment. Cyrolite HP sheet obtains an initial soft strength approximately 30–45 minutes after application. The joint will begin to “harden” approximately 3 hours after application. Joint strength will continue to increase until the joint has completely cured. As a general rule, set up time will be slightly longer than is normally required for continuously manufactured acrylic.

Cyrolite HP sheet has an improved craze resistance over extruded acrylic sheet products. As a result, Cyrolite HP sheet can often be successfully used in areas that would craze extruded acrylic sheet. This will provide a significant benefit in some applications where line bends, or flame polished edges, are adjacent to a solvent welded edge.

Reference: *Cyrolite HP Multipolymer Sheet*, Supplier design guide (1825A-695-10BP), CYRO Industries, 1994.

Cyro: Acrylite AR (features: transparent, abrasion resistant coating, 3.2 mm (0.126 inch) thick; manufacturing method: continuous cast; form: sheet)

Acrylite AR acrylic sheets are available with either one or two sides coated for protection against abrasion. When solvent welding to a noncoated sheet surface, use the same solvent or polymerizing cements commonly used for Acrylite sheet products. The most critical factor is the edge of the part to be welded. This must first be properly prepared with low stresses. Scraping, wet-sanding and buffing are acceptable methods to prepare a finished edge. Flame polishing is not recommended. Overspray from the flame may cause the surface coating to crack or craze. This may lead to delamination of the coating and a loss of abrasion resistance. Annealing of the part prior to solvent welding is recommended.

Solvent welding to a hard coated surface cannot be readily accomplished due to the chemical resistance of the coating. To solvent weld, on or to, a coated surface, the coating first must be removed by sanding or routing. When removing the coating, insure that the bonding surface is flat, clean, and free of stress. Annealing the piece will insure a stress-free surface.

Reference: *Physical Properties Acrylite AR Acrylic Sheet And Cyrolon AR Polycarbonate Sheet*, Supplier design guide (1632B-0193-10BP), Cyro Industries, 1993.

Rohm and Haas: Plexiglas

Solvent welding to flexible PVC tubing is best done with cyclohexanone, cyanoacrylates, THF (tetrahydrofuran) or a 50/50 mixture of THF/MEK (methyl ethyl ketone) containing dissolved PVC chips.

Reference: *Plexiglas Acrylic Resin from AtoHaas Clearly the Best*, Supplier marketing literature (PL-1700b), Atohaas, 1993.

Cadillac Plastic and Chemical Company: Cadco

Parts of Cadco cast acrylic are easily solvent welded together, or to other materials. Solvents are often used to bond Cadco cast acrylic because it is soluble in chlorinated and aromatic hydrocarbons. When used properly, they produce strong and transparent welded joints. Typical solvents include ethylene dichloride and trichloroethylene. Stronger, more durable joints are made with proprietary cements that require curing. These cements are usually made of the same methyl methacrylate materials as the cast acrylic parts, and may be thickened with acrylic chips to fill joints or make fillets.

Reference: *Cadco Engineering Plastics*, Supplier design guide (CP-200-92), Cadillac Plastic and Chemical Company, 1992.

Cyro: Cyrolite G20 (features: transparent)

In tests conducted to evaluate the bondability/compatibility of plasticized PVC tubing to rigid, transparent thermoplastics, acrylic provided the highest overall bond strengths of materials tested. The only problem initially observed with blends containing 80% or more of methylene chloride was that assembly became more difficult. The same held true for acetone, although, in that case, the difficulty of assembly became prohibitive. No crazing was observed for any of the solvents. Based on the test results, either a 50:50 blend of methylene chloride in cyclohexanone or a 50:50 blend of MEK in cyclohexanone is suggested as the solvent for use with acrylic.

Reference: Haskell A: Bondabilitly/compatibility of plasticized PVC to rigid, transparent thermoplastics. ANTEC 1989, Conference proceedings—Society of Plastics Engineers, New York, May 1989.

Cyro: Acrylite GP (manufacturing method: cell cast process; form: sheet)

Acrylite GP sheet can be solvent welded using common solvents or polymerizable cements. The most critical factor is the edge of the part to be cemented. The edge must have been properly machined so as to have a square flat surface and no stresses. Annealing of the part prior to solvent welding is recommended. Solvent and solvent fumes should not contact formed or polished surfaces.

Reference: *Physical Properties of Acrylite GP Acrylic Sheet*, Supplier design guide (1235D-1192-10BP)—CYRO Industries, 1988.

Aristech: Acrysteel M; Altair Plus (features: transparent; manufacturing method: continuous cast; form: sheet); **Aristech 300** (features: transparent; manufacturing method: continuous cast; form: sheet); **Aristech GPA** (features: transparent; manufacturing method: continuous cast; form: sheet); **Aristech IGP** (features: transparent; manufacturing method: continuous cast; form: sheet); **Aristech IMA**

Strong, transparent joints can be obtained in bonding sections of Aristech acrylic sheet together by giving careful attention to preparation of the mating surfaces, proper choice of solvent, and by following correct application techniques.

The heat generated by machining operations and/or thermoforming at reduced temperatures will often induce internal stresses which make the material susceptible to crazing after contact with solvents and certain cements. Such stresses can be avoided by the proper choice of thermoforming or machining conditions, or can be relieved by heat treatment.

Surfaces to be joined should be clean and fit together with uniform contact throughout the joint. In order to obtain close-fitting edges, which is especially important, it may be desirable to accurately machine the mating surfaces. Edges to be solvent welded should never be polished, as this tends to round the corners and decrease the contact area in the joint. There are several types of joints that may be used, the selection of which will usually depend upon the end-use application.

For the best strength in a solvent welded joint, the contact area should be as large as possible. Where two curved surfaces are to be joined, each should have the same radius to provide a uniform contact over the entire joint area.

Sections of Aristech GPA, IGP, or IMA can be welded together with one of the three general types of solvent commercially available—the plain solvent type, the monomer-polymer-solvent type, or the monomer-polymer-catalyst type. Aristech 300, Acrysteel M, or Altair Plus (surface) can only be joined together with the monomer–polymer solvent type or the monomer-polymer-catalyst type, since these products are highly solvent-resistant, partially cross-linked, continuous-cast acrylic sheet.

Plain Solvents: Plain solvents are the easiest and most convenient type to use. The solvents soften the mating surfaces so that complete fusion can be achieved at the interface of the joints, which then harden into a transparent bond by diffusion and by evaporation. Ordinarily, the joints require no post-treatment.

Several types of satisfactory solvents are: Weld-On 3, Weld-On 4, and methylene chloride acetone. Glacial acetic acid and chloroform are used but are not recommended, as their strong solvent action on acrylics can cause crazing. Solvents allow rapid assembly, yield medium-strength joints, and have only poor to fair outdoor weathering resistance.

Monomer-Polymer-Solvent Type Cements: These types of cements usually consist of methyl methacrylate monomer, methyl methacrylate polymer, and assorted solvents. M-P-S-type cements available are Weld-On 16 (High Viscosity) and Weld-On 35 (Low-Viscosity). M-P-S cements do not allow rapid assemblies. Usually 15–30 minutes after cement is applied, a part can be handled very carefully. High- to medium-strength joints are obtained, which have good to fair weathering resistance.

Monomer-Polymer-Catalyst Type Cements: These type of cements consist of methyl methacrylate monomer, methyl methacrylate polymer (Part A) and a catalyst (Part B). M-P-C cements available are Weld-On 40 and PS-30. These type of cements yield excellent bond strengths and weathering resistance. Assembly are slow.

Solvents and cements can be applied to parts fabricated from Aristech acrylic sheet GPA or IGP by a soak, dip, syringe, or brush method. Aristech I-300 acrylic sheet cannot utilize the soak or dip methods since it cannot be used with solvent welding. The best method depends on the type of joint to be mated, the physical configurations of parts, etc.

Temperature and humidity can affect the quality of solvent welded joints. Aristech acrylic sheet should not be solvent welded at temperatures below 18°C (65°F), over 35°C (95°F), or when the relative humidity is over 60%. Excessive moisture can cause cloudy joints that are usually weaker than normal.

When hollow articles are solvent welded, enclosed areas should be vented to prevent entrapment of solvent vapors, which could promote crazing of the acrylic.

Before a solvent weld sets, small crevices or voids can be filled by inserting cement with a hypodermic syringe.

For maximum bond strength, jigs or clamps should be used to hold the joint together with uniform pressure, no greater than 6 psi (0.04 MPa), while the joint is setting. No part of the jig or clamp should be allowed to touch the joint, because capillary action will draw the solvent under the jig, resulting in its being attached to the joint.

The solvent welded joint should be thoroughly hardened before polishing, sanding, or machining. Thermoforming should be done prior to solvent welding operations whenever possible. If thermoforming must be done on prewelded joints, a monomer-polymer catalyst-type cement should be used and the joint annealed to provide maximum bond strength during the forming operation. A close fitting "V" joint generally gives the best cemented bond for thermoforming.

Often it is desirable to solvent weld parts made from Aristech acrylic sheet to other materials such as metal, wood, other plastics, etc. IPS Corporation (455 West Victoria Street, Compton, CA 90220, USA), manufacturer of Weld-On cements, has a complete line of products for these types of jobs. Consult IPS for recommendations.

Reference: *Aristech Acrylic Sheet Technical Bulletin 136—Cementing*, Supplier technical report (ADARIS 50-1032-01), Aristech Chemical Corporation, 1987.

Cyro: Acrylite

Because of the internal stresses that occasionally occur in injection-molded parts, crazing may occur as the result of solvents used during bonding. In order to avoid this, the molding should be annealed before bonding.

Solvents such as methylene chloride can be used for bonding Acrylite molding compound to acrylics or other materials. The possibility of subsequent crazing is reduced if the design of the joint allows the solvent to escape.

Reference: *Acrylite Acrylic Molding & Extrusion Compounds*, Supplier marketing literature (1066C-1090-10CG), CYRO Industries, 1986.

Rohm and Haas: Plexiglas 55 (applications: aircraft glazing; features: biaxially stretched, craze resistant); **Plexiglas G** (features: general purpose grade); **Plexiglas K** (features: thermoformable; form: continuous process sheet)

The solvents used for joining Plexiglas G to Plexiglas G plastic soften the plastic surface. When pressed together, the softened surfaces intermingle, and form a hard joint upon the evaporation of the solvent. There are three basic methods of solvent welding Plexiglas plastic to Plexiglas plastic:

(1) Capillary or surface tension application of a solvent such as methylene chloride with a brush, pipe cleaner, or eye dropper to the butted edges to be joined. This produces quick, clean joints of low strength, for parts to be used indoors.

(2) Soak-cementing using a monomer-solvent mixture such as Rohm and Haas Cement II for medium- to high-strength joints, to be used

indoors or outdoors. The smaller piece, masked except for the area to be cemented, is soaked in the cement for approximately 3–5 minutes until the surface is softened. The two pieces are then assembled quickly before the cement on the soaked piece evaporates. High strength, soak-cemented joints are obtained by heat curing (annealing).

(3) Reactive cements such as Cement PS-30 for high-strength structural parts. These may be cured at room temperature and further improved by annealing. PS-30 is a viscous liquid and is applied to one or both of the parts to be joined. These cements should be used for Plexiglas K and 55 plastics.

Reference: *Plexiglas Acrylic Sheet General Information*, Supplier technical report (PL-1p), Rohm and Haas Company, 1985.

20.9 Adhesive Bonding

ICI: Perspex CP80

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 20.3 give a good indication of the typical bond strengths that can be achieved as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually, the results of which are given in Table 20.3, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 instant adhesive, Flashcure 4305 light cure adhesive and Super Bonder 414 instant adhesive created bonds that were stronger than the acrylic substrate for most of the formulations evaluated. Loctite 3105, a light curing acrylic adhesive, Loctite 3030 adhesive, Hysol E90-FL epoxy adhesive and Hysol U-05FL urethane adhesive normally achieved the second-highest bond strengths. Hysol 3651 and 7804 hot melt adhesives and 5900 flange sealant achieved the lowest bond strengths on PMMA. When using Black Max 380 instant adhesive, the addition of lubricant or antistatic agents resulted in the bond strengths increasing from average strengths to substrate failure.

Surface Treatments: The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused a statistically significant decrease in the bond strengths achieved on all the formulations of acrylic that were evaluated, with the exception of the flame retarded formulation. Surface roughening caused a statistically significant increase in bond strengths achieved when using Black Max 380, but caused either no effect, or a statistically significant decrease in bond strength for all the other adhesives evaluated.

Other Information: Acrylics can be stress cracked by uncured cyanoacrylate adhesives, so any excess adhesive should be removed from the surface immediately.

Table 20.3. Shear Strengths of Perspex CP80 Acrylic to Acrylic Adhesive Bonds Made Using Adhesives Available from Loctite Corporation.[b]

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	3 rms	600 (4.1)	>3950[a] (>27.2)[a]	250 (1.7)	>2900[a] (>20.0)[a]	1150 (7.9)	1750 (12.1)
Roughened	34 rms	1500 (10.3)	2150 (14.8)	400 (2.8)	>2900[a] (>20.0)[a]	650 (4.5)	1750 (12.1)
Antioxidant	0.1% Irganox 245	1400 (9.7)	>3950[a] (>27.2)[a]	350 (2.4)	>2900[a] (>20.0)[a]	1150 (7.9)	1750 (12.1)
UV stabilizer	0.6% Uvinal 3039	1450 (10.0)	>3950[a] (>27.2)[a]	250 (1.7)	>2900[a] (>20.0)[a]	1150 (7.9)	1750 (12.1)
Flame retardant	17% Phoschek P-30	1050 (7.2)	>5050[a] (>34.8)[a]	>5250[a] (>36.2)[a]	>2900[a] (>20.0)[a]	1150 (7.9)	1750 (12.1)
Lubricant	5% Witconol NP-330	>3050[a] (>21.0)[a]	>3950[a] (>27.2)[a]	350 (2.4)	>4550[a] (>31.4)[a]	1150 (7.9)	1250 (8.6)
Impact modifier	29% Paraloid EXL 3330	1250 (8.6)	>3950[a] (>27.2)[a]	1250 (8.6)	2900 (20.0)	650 (4.5)	1750 (12.1)
Plasticizer	9% Benoflex 50	600 (4.1)	>3000[a] (>20.7)[a]	250 (1.7)	>2900[a] (>20.0)[a]	1150 (7.9)	1750 (12.1)
Colorant A	1% OmniColor Pacific Blue	1550 (10.7)	>3350[a] (>23.1)[a]	250 (1.7)	>2900[a] (>20.0)[a]	1150 (7.9)	1350 (9.3)
Colorant B	0.5% 99-41-042 green	600 (4.1)	>2350[a] (>16.2)[a]	250 (1.7)	>2900[a] (>20.0)[a]	450 (3.1)	1750 (12.1)
Antistatic	1.5% Markstat AL-48	>2150[a] (>14.8)[a]	>3950[a] (>27.2)[a]	250 (1.7)	>2900[a] (>20.0)[a]	1150 (7.9)	1750 (12.1)

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses)

Acrylics are compatible with acrylic adhesives but can be attacked by their activators before the adhesive has cured. Any excess activator should be removed from the surface immediately. Acrylics are incompatible with anaerobic adhesives. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner and Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

Altuglass International: Plexiglas

Plexiglas acrylic resins are compatible with a wide variety of commonly used adhesives, including polyester, epoxy, cyanoacrylates, and nitrile-phenolics.

Reference: *Plexiglas Technical Data. Welding Methods. Chemical Methods*, Supplier technical data sheet, Altuglass International, 2006.

Acrylic

Acrylic can be bonded using anaerobic, cyanoacrylate, UV, epoxy and structural acrylic adhesives. Light abrasion can help.

Reference: *The Engineers Guide to Adhesives*, Supplier design guide, Permabond Engineering Adhesives.

Rohm and Haas: Plexiglas

The flexibility of Plexiglas acrylic permits it to be bonded to dissimilar amorphous resins such as ABS, PC, SAN, and polyesters. Plexiglas resins may also be bonded to PVC tubing with cyanoacrylate and bonds well with UV-curable adhesives.

Reference: *Plexiglas Acrylic Resin from AtoHaas Clearly the Best*, Supplier marketing literature (PL-1700b), Atohaas, 1993.

Cyro: Acrylite

Because of the internal stresses that occasionally occur in injection-molded parts, crazing may occur as the result of solvents used during bonding. In order to avoid this, the molding should be annealed before bonding.

Polymerizing adhesives can be used for bonding Acrylite molding compound to acrylics or other materials. These are two component adhesives with exceptional bond strength, good body and very good weather resistance. Contact adhesives, mainly neoprene-based, are suitable for bonding Acrylite to materials such as leather or wood.

Reference: *Acrylite Acrylic Molding & Extrusion Compounds*, Supplier marketing literature (1066C-1090-10CG), CYRO Industries, 1986.

20.10 Mechanical Fastening

Altuglass International: Plexiglas

Plexiglas acrylic resins may be heat staked for assembly to materials to which it cannot be welded, for example, metals and crystalline polymers. Staking is readily accomplished using heat or ultrasonic energy.

Reference: *Plexiglas Technical Data. Welding Methods*, Supplier technical data sheet, Altuglass International, 2006.

21 Cellulosics

21.1 Adhesive Bonding

Eastman Performance Plastics: Tenite 3754000012

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens.

Table 21.1. Shear Strengths of Tenite 3754000012 Cellulose Acetate Propionate (CAP) to CAP Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[c]

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive General Purpose)	**Depend 330** (Two-Part No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	3 rms	400 (2.8)	1950 (13.5)	2150 (14.8)	1550 (10.7)	1200 (8.3)	1850 (12.8)
Roughened	19 rms	400 (2.8)	1950 (13.5)	1550 (10.7)	1550 (10.7)	900 (6.2)	1850 (12.8)
Antioxidant	0.15% Irganox 1010	400 (2.8)	1950 (13.5)	2150 (14.8)	1550 (10.7)	700 (4.8)	1850 (12.8)
UV stabilizer	0.2% Chimasorb 994	400 (2.8)	>2450[a] (>16.9)[a]	2000 (13.8)	2000 (13.8)	550 (3.8)	1850 (12.8)
Flame retardant	17% Reofos 35	250 (1.7)	1350 (9.3)	1000 (6.9)	900 (6.2)	650 (4.5)	1300 (9.0)
Plasticizer	9% Benzoflex 988	250 (1.7)	1050 (7.2)	1200 (8.3)	1150 (7.9)	650 (4.5)	1500 (10.3)
Lubricant	0.1% Zinc Stearate	250 (1.7)	1950 (13.5)	2150 (14.8)	750 (5.2)	350 (2.4)	1850 (12.8)
Filler #1	17% 497 Fiberglass	400 (2.8)	1950 (13.5)	>2200[a] (>15.2)[a]	1550 (10.7)	650 (4.5)	>1900[b] (>13.1)[b]
Filler #2	17% Omyacarb F $CaCO_3$	650 (4.5)	>1950 (>13.5)	>2150[a] (>14.8)[a]	1550 (10.7)	1200 (8.3)	>1600[b] (>11.1)[b]
Colorant	1% Green	400 (2.8)	1950 (13.5)	2150 (14.8)	1550 (10.7)	850 (5.9)	1850 (12.8)
Antistatic	1.5% Markstat AL-12	1700 (11.7)	>2200[a] (>15.2)[a]	1800 (12.4)	>2450[a] (>16.9)[a]	400 (2.8)	>2250[a] (>15.5)[a]

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] Due to the severe deformation of the block shear specimens, testing was stopped before the actual bond strength achieved by the adhesive could be determined (the adhesive bond never failed).

[c] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches/second (0.25 mm/s).

While the bond strengths in Table 21.1 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually, and the results are displayed in Table 21.1, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in “real world” applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and the price will play a large role in determining the optimum adhesive system for a given application.

Adhesive performance: Loctite 3340 light cure adhesive, 3030 adhesive and Fixmaster high performance epoxy all created bonds that were stronger than the standard grade of cellulose acetate propionate (CAP) tested. Prism 401 and Super Bonder 414 instant adhesives, Flashcure 4305 and 3105 light cure adhesives, and Hysol 3631 hot melt adhesive typically achieved the next highest bond strengths on CAP. Depend 330 adhesive, Hysol E-00CL, E-30CL and E-20HP epoxy adhesives, and Hysol U-05FL urethane adhesive performed exceptionally as well.

Surface treatments: Prism Primer 770, when used in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive used with Prism Primer 7701, had no overall statistically significant effect on the formulations of CAP that were evaluated. However, it did cause a statistically significant decrease in bond strengths achieved on the UV stabilized and antistatic formulations and a statistically significant increase for the glass and calcium carbonate-filled formulations. Surface roughening caused either no effect, or a statistically significant decrease in the bondability of CAP.

Other information: Cellulosics can be stress cracked by uncured cyanoacrylate adhesives, so any excess adhesive should be removed from the surface immediately. Cellulosics are compatible with acrylic adhesives, but can be attacked by their activators before the adhesive has cured. Any excess activator should be removed from the surface immediately. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner and Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4,* Supplier design guide, Loctite Corporation, 2006.

22 Fluoroplastics

22.1 Polyvinylidene Fluoride

22.1.1 General

Solvay: Solef

Items produced from all nonreinforced grades of Solef PVDF can be easily assembled using standard welding methods such as hot air welding with welding rod; polyfusion (butt or socket welding); heat-sealing; ultrasonic; vibration; friction; dielectric heating (high frequency) or solvent bonding.

Reference: *Solvay Polyvinylidene Fluoride*, Supplier design guide (B-1292c-B-2.5-0390), Solvay, 1992.

22.1.2 Heated Tool Welding

Solvay Solexis: Solef, Hylar

The mating parts are heated by pressing onto a metal heater which is held at 250–270°C (482–518°F) and which has been surface treated (usually with PTFE) to minimize adhesion. The ideal pressure on the hot surface is 0.5–0.6 bar (7.3–8.7 psi; 0.05–0.06 MPa), and the time should be sufficient for the fusion of the material to a depth of 4–5 mm (0.16–0.20 inches) at the contact surface. The heating unit is then removed and contact is made under a pressure of ideally 0.6–0.8 bar (8.7–11.6 psi; 0.06–0.08 MPa). Welding factors obtained by this technique are generally between 0.9 and 1.

Reference: *Solef & Hylar PVDF Design and Processing Guide*, Supplier design guide (BR2001C-B-2-1106), Solvay Solexis, 2006.

PVDF [form: 110 mm (4.3 inch) diameter pipe, 5.3 mm (0.2 inch) wall thickness]

An investigation into the technology and strength of butt pressure-welded tubular joints showed that all three welding parameters (temperature of heating element, contact pressures during preheat and cooling, and heating time) had a significant effect on the properties of the joints.

The quality of the joint was assessed on the basis of visual examination, static tensile, and bend tests. The best results were obtained when the main heating period was between 93 and 123 seconds. Shorter and longer periods both reduced the bend angle. Although the strength factor of the joint was acceptable, varying from 0.90–0.98, the flash produced was too high.

The temperature of the heating element varied within the limits of 220°C (428°F) and 250°C (482°F). Consideration of the strength results led to the conclusion that the temperature of 220°C (428°F) was unfavorable because the bend angle was well below the minimum allowable value, and the strength factor was 0.85. At a heating element temperature of 250°C (482°F), some of the bend angles were also lower than the minimum allowable value. It follows therefore, that the most advantageous temperature range for the heating element lies between 230°C (446°F) and 240°C (464°F). Changing the magnitude of the contact pressure also had a significant effect. The contact pressure should be 5 bar (0.5 MPa; 72.5 psi).

Reference: Dziuba S: Effect of parameters of the butt pressure welding process on the strength and ductile properties of polyvinylidene fluoride (PVDF)-tubular joints. *Welding International*, 17(11), p. 845, 2003.

Symalit: PVDF

For heated element welding, the temperature of the mirror should be 230–240°C (446–464°F). The fusion pressure (and welding pressure) should be 11.4 psi (80 kPa). The heating-up period should be about 20 seconds. The heated element (mirror) should be coated with PTFE to prevent the materials to be welded from sticking. Normal welding factors of 0.8–1.0 should be achieved.

Reference: *The Welding of Symalit—PVDF and Symalit-PVDF Flex Semifinished Products*, Supplier guide, Symalit.

22.1.3 Ultrasonic Welding

Solvay: Solef

Ultrasonic welding can be used to weld parts made from all grades of Solef PVDF including copolymers or alloys, reinforced or not. The standard procedure for crystalline polymer welding by ultrasonic techniques (geometry of weld joint, type of booster, and horn) can be applied for all elements made from Solef PVDF.

Reference: *Solvay Polyvinylidene Fluoride*, Supplier design guide (B-1292c-B-2.5-0390), Solvay, 1992.

22.1.4 Vibration Welding

Elf Atochem: Kynar 720 (features: homopolymer); **Kynar Flex-2800** (features: random copolymer with hexafluoropropylene)

The welding machine used in this study was equipped with a displacement transducer that allowed for the measurement of weld penetration versus time. Data were obtained under the same processing conditions (frequency = 60 Hz, amplitude = 0.85 mm (0.033 inches), pressure = 75 psi (0.52 MPa)).

Results showed that the first phase, where no penetration occurs, is shorter for the copolymer (6 s), compared to the homopolymer (13 s). This is a direct consequence of lowered melting temperature in the copolymer (150°C (302°F) compared to 177°C (351°F) for the homopolymer).

In the PVDF copolymer, two additional steps are observed; one rather fast, followed by a slower stage. In the homopolymer this two stage penetration is absent; instead it is a gradual increase to a steady state value. These differences can be attributed to the differences in the melt viscosities of the two grades. The standard viscosity of PVDF copolymer is between 22×10^3 and 27×10^3 poise, while the range for PVDF homopolymer is between 8×10^3 and 12×10^3 poise. Therefore, once this phase takes place and the material starts melting, the copolymer produces more shear stresses due to the higher viscosity and the vibration motion, generating more energy to melt the polymer; so a faster penetration rate is attained.

Once the steady state is achieved (third phase of the process), a larger slope in the penetration-time curve is observed for the PVDF homopolymer. This is because its lower viscosity in the melt allows the extrusion of the material more easily to the sides of the HAZ under the action of the normal force.

Reference: Valladares D, Cakmak M: Heat affected zone structure in vibration welded polyvinylidene fluoride and its copolymer. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

22.1.5 Spin Welding

Solvay: Solef

Solef PVDF parts are easily welded using spin welding. A practical check is that Solef changes from opaque to transparent when it melts. Welding factors thus obtained are between 0.7 and 0.8.

Reference: *Solvay Polyvinylidene Fluoride*, Supplier design guide (B-1292c-B-2.5-0390), Solvay, 1992.

PVDF (form: cylinder)

In spin welding, the weld initiation time (WIT) consists of Stage I and Stage II and decreases with axial pressure. The WIT is found to be 1.5s at 2.0 MPa (290 psi), 0.75s at 4.3 MPa (624 psi), and less than 0.25 seconds at 6.8 MPa (986 psi). All of these effects may be attributed to the increased temperature rise, hence, to melting rates, which occur at higher pressures.

A distinct increase in weld penetration results from an increase in axial pressure. The rotational speed yields a similar behavior as the weld penetration increases steadily with increasing rotational speed. The effects of normal force and rotation speed are also highly nonlinear.

For a longer test duration, axial pressure and rotational movement are maintained for a longer period of time. This allows more melting and thus, greater weld penetration for increased test duration. This increase in weld penetration with increasing test duration appears to be quite linear in most cases. The final weld penetration increases with increasing rotational speed and increasing axial pressure.

The axial pressure is shown to have a greater effect on the WIT, while the rotational speed affects only the WIT moderately. At 3000 rpm, the WIT is reduced from 1.5 seconds to 0.25 seconds when the axial pressure is increased from 2.0 MPa (290 psi) to 6.8 MPa (986 psi). At 4.3 MPa (624 psi), the WIT is only reduced from 1.0 seconds to 0.7 seconds when the rotational speed is increased from 2000 rpm to 3500 rpm.

For each axial pressure condition, as the rotational speed is increased, the weld strength reaches a maximum value before diminishing. At low axial pressure, the bonding of the samples does not occur at low rotation speeds for 3.4 seconds weld duration and high-strength welds can only be achieved at high rotation speed. In this case, we also see a peak in the strength data. At high axial pressures, good welds could be formed at rotation speeds down to 2000 rpm (this is the lowest rotation speed utilized in the experiments), and at each normal force a peak is observed, the magnitude of which appears to decrease with further increase in axial pressure. This may be related to the formation of very high chain orientation primarily aligned in the weld plane in the hoop direction.

Reference: Schaible S, Cakmak M: Instrumented spin welding of polyvinylidene fluoride. ANTEC 1992, Conference proceedings, Society of Plastics Engineers, Detroit, May 1992.

22.1.6 Hot Gas Welding

Solvay Solexis: Solef, Hylar

The parts to be welded are profiled. After cleaning, they are clamped in place. The air is heated in the hot air gun. The air temperature, taken 5 mm (0.197 inches) from the end of the nozzle, can be around 350°C (662°F). The welding rod is inserted into the bevel, maintaining a continuous vertical pressure of 0.2–0.4 bar (2.9–5.8 psi).

The welding factor, which is generally defined as the ratio between the strength of the weld and the strength outside the welded zones, gives values between 0.9 and 1.0.

Reference: *Solef & Hylar PVDF Design and Processing Guide*, Supplier design guide (BR2001C-B-2-1106), Solvay Solexis, 2006.

PVDF (form: sheet)

The following welding conditions are recommended for PVDF: temperature of 350–400°C (662–752°F), force (for a 4 mm (0.157 inch) diameter welding rod) of 25–35 N (5.6–7.9 lbf) and a gas flow of 40–60 l/minute.

Reference: Gibbesch B: Thermoplastic inliner for dual laminate constructions. Welding Beyond Metal: AWS/DVS Conference on Plastics Welding, New Orleans, March 2002.

Symalit: PVDF

As PVDF does not oxidize, air may be used for welding. The temperature of the welding air should be (measured 5 mm (0.197 inches) in front of the nozzle end) between 350–360°C (662–680°F). The necessary air volume is about 50–60 l/minute. The recommended welding pressures and welding speeds are given in Table 22.1.

Cleaning the material and welding rod prior to welding is advisable.

Normal welding factors of 0.8–1.0 are achievable.

Reference: *The Welding of Symalit-PVDF and Symalit-PVDF Flex Semi-finished Products*, Supplier guide, Symalit.

22.1.7 Extrusion Welding

Solvay: Solef

With extrusion welding, the support is prepared (beveled or preferably double beveled) and preheated using a hot air gun to reach a surface temperature of 250–260°C (482–500°F). The molten extrusion (maximum length—20 cm) is pressed into the bevel using stainless steel or PTFE-coated tools.

The weld factor, which is generally defined as the relation between the strength of the weld and the strength outside the welded zones, determined by tensile stress tests, will give values between 0.8–0.9.

Reference: *Solvay Polyvinylidene Fluoride*, Supplier design guide (B-1292c-B-2.5-0390), Solvay, 1992.

22.1.8 Infrared Welding

PVDF

Experiments have shown that a range of welding parameters can be used to reach the maximum weld quality, with melt depth and joining distance being the determining parameters. The melt depth is fixed by the energy going into the joint, and this is a function

Table 22.1. Symalit PVDF Hot Gas Welding Pressures and Welding Speeds

	Welding Force, N (lbf)	Welding Speed, cm/min (inches/min)
For normal round section nozzles	10–15 (2.25–3.37)	10–15 (3.9–5.9)
For speed nozzles	~20 (4.5)	25–40 (9.8–15.7)

of the nature of heater, temperature, exposure time, geometry of the welding assembly, and the polymer to be melted.

The mechanical testing conducted on the high quality infrared welds has shown that the welding factors achieved for PVDF when tested at –40°C (–40°F) were greater than 0.9.

Reference: Taylor NS, Klaiber F, Wermelinger J: Assessment of PP and PVDF joints made by a new infrared jointing system. ANTEC 1993, Conference proceedings, Society of Plastics Engineers, New Orleans, May 1993.

22.1.9 Microwave Welding

PVDF (form: pipe)

Pipes and fittings made of PVDF can be welded by microwaves. This microwave welding technology includes several benefits: the energy needed to melt the plastic can be applied with precision and accuracy, focusing the field intensity allows a reduction in energy input, and the energy source need not be activated any longer than required for heating as the power is available immediately and in the necessary volume.

Power consumption reached no higher than 250 W for a pipe dimension of 32 mm (1.25 inches) outside diameter. The ratio of joint strength to base material strength was at least 0.8.

A major advantage of this new technology is that it provides precise control of the bead; bead formation can be modified so that the inside beads are minimized without degradation.

Reference: Dommer M: Using microwaves to weld PVDF pipes and fittings. *Welding Journal*, 80(1), p. 35, January 2001.

22.1.10 Solvent Welding

Solvay: Solef

Solef PVDF parts can be welded using a Solef 2010 powder-base bonding agent, dissolved in a polar solvent such as dimethylformamide. This technique, which at first sight appears easy to apply, nevertheless has certain disadvantages, mainly due to:

- The characteristics of the solvent used:
  - high boiling point (>150°C; 302°F), low vapor pressure, difficult to eliminate,
  - presents health hazards,
  - poor dissolving power, hence dry matter is limited (25% w/w).
- The difficulty of ensuring control and measuring the complete elimination of the solvent, which, when present, can considerably diminish the strength of the weld.

Reference: *Solvay Polyvinylidene Fluoride*, Supplier design guide (B-1292c-B-2.5-0390), Solvay, 1992.

22.2 Polytetrafluoroethylene

22.2.1 Infrared Welding

DuPont: Teflon PTFE [form: 4.8 mm (0.19 inch) thick sheet]

There have been rare reports where heated tools at high temperatures were used to weld PTFE but these attempts involved decomposition of the polymer on the heated tool and the welds were made through the decomposed polymer. Resulting joints were weak and the fumes from the process are very hazardous to personnel in the area.

In this study, a strap joint configuration was used, as shown in Fig. 22.1.

The weld patch with the carbon black pigmented Teflon PFA interlayer was supported by screws through the support base of the fixture so the weld patch could be accurately fitted against the PTFE coupons. Welding was conducted using a 500 W quartz-halogen lamp that was 38 mm (1.5 inches) wide and 150 mm (5.9 inches) long. Full voltage (120 V) was applied during the heating phase, but it was reduced in steps to maintain a constant temperature.

Results showed that the transparency of PTFE to infrared radiation allows it to be readily welded using an absorbing layer of Teflon PFA that contains a low level of carbon black. Weld strengths of strap joints exceeded the strength of the coupons used to make the joints. Some of the best welding conditions were with a 0.4 mm (0.016 inch) thick, 0.3% carbon-loaded PFA interlayer, and a welding temperature of 340°C (644°F). PFA films with lower levels of carbon black (0.03% and 0.003%) were more transparent to the infrared energy and welding was facilitated on both sides of the film interlayer simultaneously.

Reference: Grimm RA: Through-transmission infrared welding (TTIR) of Teflon® TFE (PTFE). ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

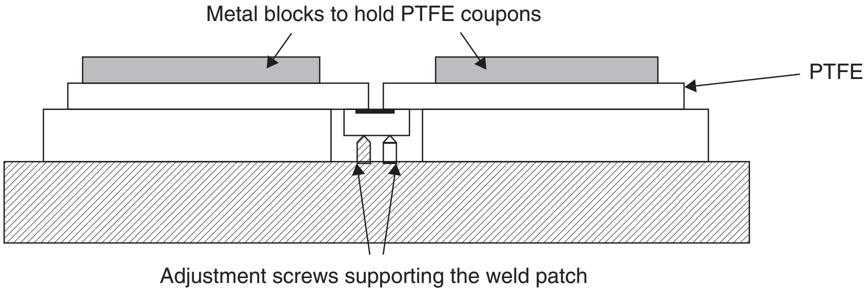


Figure 22.1. Strap joint configuration.

22.2.2 Adhesive Bonding

DuPont: Teflon PTFE

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 22.2 give a good indication of the typical bond strengths that can be achieved they also face several limitations. For example, a consideration that must be kept in mind when using this data to select a suitable adhesive is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 instant adhesive used in conjunction with Prism Primer 770 and 3030 adhesive, achieved the highest bond strengths on unetched PTFE. Prism 4011 and Super Bonder 414 instant adhesives typically achieved the next highest bond strengths. The bond strengths achieved on the unfilled/untreated resin can generally be described as poor for all other adhesives evaluated.

Surface Treatments: Acton FluoroEtch and Gore Tetra-Etch both caused large, statistically significant increases in the bond strengths achieved on PTFE. Surface roughening caused either no effect or small, statistically significant increases in the bond strengths achieved on PTFE. The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused a statistically significant increase in the bondability of unprimed PTFE. Neither UV-ozone treatment nor plasma treatment caused an increase in the bondability of PTFE.

Other Information: PTFE is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner and Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

Saint-Gobain: Rulon

The Rulon or PTFE material should be purchased with one side etched for bonding. The side will be dark brown or blackish in color. The etched Rulon or PTFE surfaces should be washed (flushed) with acetone, and air-dried prior to coating with the adhesive. Adhesives should be of epoxy resin type. The

Table 22.2. Shear Strengths of Teflon PTFE to PTFE Adhesive Bonds Made Using Adhesives Available from Loctite Corporation*

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	88 rms	200 (1.4)	350 (2.4)	1050 (7.2)	300 (2.1)	100 (0.7)	150 (1.0)
Roughened	349 rms	200 (1.4)	350 (2.4)	800 (5.5)	700 (4.8)	250 (1.7)	300 (2.1)
Teflon treated with Acton Fluoro Etch		950 (6.6)	1800 (12.4)	1550 (10.7)	1750 (12.1)	450 (3.1)	750 (5.2)
Teflon treated with Gore Tetra Etch		1350 (9.3)	1900 (13.1)	1200 (8.3)	1800 (12.4)	350 (2.4)	700 (4.8)

*All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (parentheses).

epoxy resin should be of medium viscosity, which will facilitate spreading without too much sagging. Both surfaces should be coated using a doctor blade to produce an even coating and the coating thickness should be approximately 0.002–0.004 inches (0.05–0.10 mm). Both parts should then be placed together immediately. Some means of clamping these components together must be provided. The clamping pressure used can be from 10 to 100 psi (0.07–0.7 MPa), with 50 psi (0.34 MPa) being the optimum.

Reference: *Rulon and PTFE Bearings—Bonding Techniques*, Supplier design guide, Saint-Gobain Performance Plastics, 2001.

Cadillac Plastic and Chemical Company: Cadco Teflon

The nonstick and/or solvent resistant nature of Cadco Teflon requires that part surfaces be specially prepared before adhesive bonding can occur. The surfaces can then adhere to like substrates or others such as wood, steel, and aluminum.

Cadco Teflon must be thoroughly cleaned with acetone or a similar solvent to remove grease and other contaminants. Next, a sodium acid or other etching solution is used. To eliminate these steps toward bondability, PTFE sheet can be provided with one or both sides already etched for bonding.

Reference: *Cadco Engineering Plastics*, Supplier design guide (CP-200-92), Cadillac Plastic and Chemical Company, 1992.

22.3 Ethylene Chlorotrifluoroethylene

22.3.1 Hot Gas Welding

Solvay Solexis: Halar ECTFE

When hot gas welding Halar ECTFE, use welding guns with a heating power of 800 W or higher. Good quality Halar ECTFE welds can be obtained when nitrogen or clean and dry air is used. Welding in nitrogen is recommended when the welding facility lacks a clean and dry source of air.

Use round welding rods made of the same Halar grade as the profiles to be welded. Welding together profiles made from different grades is not recommended.

Adjust the air flow to 50–60 standard liters per minute, and set the temperature of the welding gun as indicated in Table 22.3.

Welding speeds of 0.1–0.5 cm/second (0.04–0.20 inches/second) are usually suitable.

Excessive heating may produce fumes and gases that are irritating or toxic. Ventilation, or proper breathing equipment should be provided to prevent exposure to fumes and gases that may be generated.

Table 22.3. Halar ECTFE Hot Gas Welding Temperatures (Measured Inside the Nozzle)

Halar ECTFE grade	Welding gun temperature
901, 300, 350, 500	380–425°C (716–797°F) (380–400°C; 716–752°F for thin liners)
902	425–495°C (797–923°F)

Reference: *Halar ECTFE Design and Processing Guide*, Supplier design guide (BR2003C-B-05-1106), Solvay Solexis, 2006.

ECTFE (form: sheet)

The following welding conditions are recommended for ECTFE: temperature of 350–380°C (662–716°F), force (for a 4 mm (0.16 inch) diameter welding rod) of 20–25 N (4.5–5.6 lbf) and a nitrogen gas flow of 40–60 l/min.

Reference: Gibbesch B: Thermoplastic inliner for dual laminate constructions. Welding Beyond Metal: AWS/DVS Conference on Plastics Welding, New Orleans, March 2002.

Symalit: ECTFE

The temperature of the welding gas (nitrogen) should be 350–380°C (662–716°F), (measured 5 mm (0.197 inches) in front of the nozzle end). The required gas flow is approximately 50–60 l/minute. The recommended welding pressures and welding speeds are given in Table 22.4.

Cleaning the material and welding rod prior to welding is advisable.

Reference: *The Welding of Symalit ECTFE Semi-finished Products*, Supplier guide, Symalit.

22.4 Fluorinated Ethylene Propylene

22.4.1 Hot Gas Welding

Symalit: FEP

The welding gas temperature must be accurately controlled and should not exceed 390°C (734°F) (measured 5 mm (0.197 inches) in front of the nozzle end). The material should be fabricated in a special room which can be properly ventilated. Exhaust hoods should be provided wherever welding is being done, and they should be located as close as possible to the hot polymer. Breathing apparatus with a constant supply of fresh air and providing protection for the eyes should always be worn when welding FEP. Smoking during fabrication is strictly forbidden and no cigarettes, matches, etc. must be taken into any room where material is being welded.

Reference: *Symalit FEP Pipes and Semifinished Products*, Supplier Safety Data Sheet, Symalit.

22.4.2 Adhesive Bonding

DuPont: Teflon FEP

A study was conducted to determine the bond strength of fluorinated ethylene propylene, and the adhesives best suited to it. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad.

While the bond strengths in Table 22.5 give a good indication of the typical bond strengths that can be achieved, they also face several limitations. For example, a consideration that must be kept in mind when using this data to select a suitable adhesive is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive

Table 22.4. Symalit ECTFE Hot Gas Welding Pressures and Welding Speeds

	Welding Force, N (lbf)	Welding Speed, cm/min (inches/min)
For normal round section nozzles	10–15 (2.25–3.37)	10–15 (3.9–5.9)
For speed nozzles	20 (4.5)	15–20 (5.9–7.9)

Table 22.5. Shear Strengths of FEP to FEP Adhesive Bonds Made Using Adhesives Available from Loctite Corporation*

Material Composition	Loctite Adhesive					
	Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	<50 (<0.3)	<50 (<0.3)	<50 (<0.3)	<50 (<0.3)	<50 (<0.3)	<50 (<0.3)

*All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: The bond strengths achieved for all adhesives evaluated can be described as poor.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4,* Supplier design guide, Loctite Corporation, 2006.

22.5 Perfluoroalkoxy

22.5.1 Hot Gas Welding

Solvay Solexis: Hyflon PFA

When hot gas welding PFA, use welding guns capable of good temperature control up to 650°C (1200°F) and with a heating power of 900–1000 W or higher. Use round welding rods made of the same Hyflon grade as the profiles to be welded. Welding together profiles made from different grades is not recommended.

Adjust the air flow to 50–60 standard liters/minute, and set the temperature of the welding gun as indicated in Table 22.6.

Welding speeds of 5–30 cm/minute (2–12 inches/minute) are usually suitable.

Table 22.6. Hyflon PFA Hot Gas Welding Temperatures (Measured Inside the Nozzle)

Hyflon Grade	Welding Gun Temperature
PFA M620	500–590°C (930–1100°F)
PFA P420	560–620°C (1040–1150°F)

Excessive heating may produce fumes and gases that are irritating or toxic. Ventilation or proper breathing equipment should be provided to prevent exposure to fumes and gases that may be generated.

Reference: *Hyflon PFA Design and Processing Guide*, Supplier design guide (BR2002C-B-2-1106), Solvay Solexis, 2006.

Symalit: PFA

The temperature of the welding air should be between 400–410°C (752–770°F) (measured 5 mm (0.197 inches) in front of the nozzle end). The required air flow is approximately 50–60 liters/minute. The suggested welding pressures are given in Table 22.7.

The welding speed should not exceed 7 cm/minute (2.8 inches/minute). The prepared weld and the welding rod should be cleaned with Frigen 113 before welding.

Reference: *The Welding of Symalit PFA Semi-finished Products*, Supplier Guide, Symalit.

Table 22.7. Symalit PFA Hot Gas Welding Pressures

	Welding Force, N (lbf)
For normal round section nozzles	10–15 (2.25–3.37)
For speed nozzles	~20 (4.5)

22.5.2 Adhesive Bonding

DuPont: Teflon PFA

A study was conducted to determine the bond strength of perfluoroalkoxy and the adhesives best suited to it. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad.

While the bond strengths in Table 22.8 give a good indication of the typical bond strengths that can be achieved, they also face several limitations. For example, a consideration that must be kept in mind when using this data to select a suitable adhesive is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 instant adhesive used in conjunction with Prism Primer 770, achieved the highest bond strengths on PFA. Prism 401 instant adhesive achieved the next highest bond strength. The bond strengths achieved for all other adhesives evaluated can generally be described as poor.

Other Information: PFA is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

22.6 Ethylene Tetrafluoroethylene

22.6.1 Heated Tool Welding

DuPont: Tefzel

Tefzel can be welded to itself using such techniques as hot plate welding. The bond is achieved by heating the materials to 271–277°C (520–530°F) then pressing the parts together during cooling.

Reference: *Tefzel Fluoropolymer Design Handbook*, Supplier design guide (E-31301-1), DuPont Company, 1973.

22.6.2 Ultrasonic Welding

DuPont: Tefzel

The ultrasonic welding of Tefzel has been demonstrated with weld strengths up to 80% of the strength of the base resin. The success of developments involving this technique depends upon joint design and the experimentally determined welding parameters of contact time and pressure. Typical welding conditions are 25 psi (0.172 MPa) contact pressure and a one or two-second cycle time. The two basic joint designs are the shear and butt joint. Both employ a small initial contact area to concentrate and direct the high frequency vibrational energy.

Reference: *Tefzel Fluoropolymer Resin. Properties Handbook*, Supplier design guide (H-96518-1), DuPont Fluoroproducts, 2003.

Table 22.8. Shear Strengths of Teflon PFA to PFA Adhesive Bonds Made Using Adhesives Available from Loctite Corporation*

Material Composition	Loctite Adhesive					
	Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	<50 (<0.3)	100 (0.7)	400 (2.8)	50 (0.3)	<50 (<0.3)	50 (0.3)

*All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

22.6.3 Hot Gas Welding

Symalit: ETFE

The welding gas temperature must be accurately controlled and should not exceed 395°C (743°F) (measured 5 mm (0.197 inches) in front of the nozzle end). The material should be fabricated in a special room which should be properly ventilated. Exhaust hoods should be provided wherever welding is being done, and should be located as close as possible to the hot polymer. Breathing apparatus with a constant supply of fresh air and protection for the eyes should always be worn when welding ETFE. Smoking during fabrication is strictly forbidden and no cigarettes, matches, etc. must be taken into any room where material is being welded.

Reference: *Symalit ETFE Pipes and Semifinished Products*, Supplier safety data sheet, Symalit.

22.6.4 Adhesive Bonding

DuPont: Teflon ETFE

A study was conducted to determine the bond strength of ethylene tetrafluoroethylene and the adhesives best suited to it. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad.

While the bond strengths in Table 22.9 give a good indication of the typical bond strengths that can be achieved they also face several limitations. For example, a consideration that must be kept in mind when using this data to select a suitable adhesive is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 instant adhesive used in conjunction with Prism Primer 770 and 3030 adhesive, achieved the highest bond strengths on ETFE. The bond strengths achieved for all other adhesives evaluated can generally be described as poor.

Surface Treatments: The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, caused a statistically significant increase in the bondability of ETFE.

Other Information: ETFE is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

Table 22.9. Shear Strengths of ETFE to ETFE Adhesive Bonds Made Using Adhesives Available from Loctite Corporation*

Material Composition	**Loctite Adhesive**					
	Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	50 (0.3)	100 (0.7)	>1650 (>11.4)	100 (0.7)	50 (0.3)	100 (0.7)

*All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

DuPont: Tefzel

Because of the outstanding chemical resistance of Tefzel, surface treatment is required to allow adhesive bonding. Chemical etch, corona, or flame treatments can be used to make surfaces of Tefzel receptive to adhesives. Polyester and epoxy compounds are suitable adhesives when surfaces are properly prepared.

Reference: *Tefzel Fluoropolymer Resin. Properties Handbook*, Supplier design guide (H-96518-1), DuPont Fluoroproducts, 2003.

22.6.5 Mechanical Fastening

DuPont: Tefzel

Snap-fit Assemblies: The lower ductility of Tefzel HT2004 suggests that other assembly methods be used for this product, although snap-fits are possible at low strains. A maximum strain of about 5% is suggested.

Press-fit Assemblies: With Tefzel joined to Tefzel, the press fit joint may be designed with an interference resulting in strains of 6–7%.

Tapping and Self-tapping Screws: Self-tapping screws are used for joining parts of Tefzel. Either of two types (the thread cutting, which taps a mating head as the screw is driven, or the thread forming which mechanically displaces material as the screw is driven) can reduce assembly cost. A rule of thumb is that the boss diameter should be about double the screw diameter, and the engagement length about 2.5 times the screw diameter, for maximum holding power. Lubricants should be avoided for maximum stripping torque.

Threaded Mechanical Inserts: Threaded inserts are used for joining parts of Tefzel. They can be molded in place, pressed in, or driven in ultrasonically.

Reference: *Tefzel Fluoropolymer Resin. Properties Handbook*, Supplier design guide (H-96518-1), DuPont Fluoroproducts, 2003.

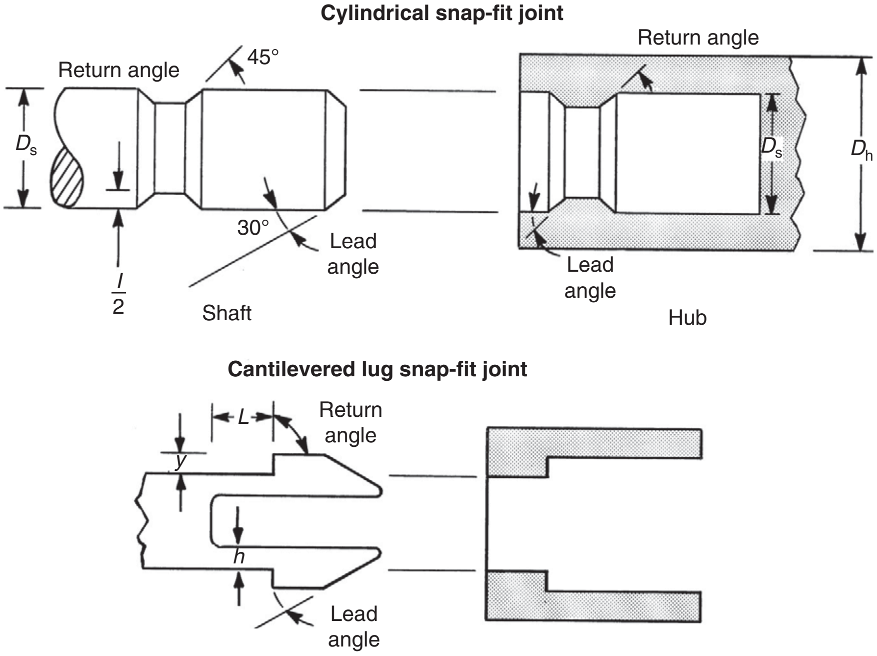
DuPont: Tefzel

Riveting: Rivets or studs can be used in forming permanent mechanical joints. The heading is accomplished with special tools and preferably with the rivet at elevated temperatures. Formed heads tend to recover part of their original shape if exposed to elevated temperatures so joints can become loose. Forming at elevated temperatures tends to reduce recovery.

Snap-fit Assemblies: The advantage of snap-fit joints is that the strength of the joint does not diminish with time because of creep. Two types of snap-fits are (Fig. 22.2):

- A cylindrical snap-fit for joining a steel shaft and a hub of Tefzel.
- A cantilevered lug snap-fit for inserting a Tefzel part into another part.

In a cylindrical snap-fit joint the maximum strain at the inside of the hub is the ratio of interference to


Cylindrical snap-fit joint

Cantilevered lug snap-fit joint

Figure 22.2. Cylindrical and cantilevered snap-fit joints.

diameter (×100 for percent). A maximum strain of about 5% is suggested. For the cantilevered lug snap-fit joint, a 5% maximum strain is also suggested.

Press-fit Assemblies: If a part of Tefzel and one of metal are to be joined, lower strain levels may be used. Assembly can often be made easier by inserting a cooled part into a heated hub.

Reference: *Tefzel Fluoropolymer Design Handbook*, Supplier design guide (E-31301-1), DuPont Company, 1973.

22.7 Modified Fluoroalkoxy

22.7.1 Hot Gas Welding

Symalit: MFA

The temperature of the welding air should be between 395–405°C (743–761°F) (measured 5 mm (0.197 inches) in front of the nozzle end). The required air flow is approximately 50–60 l/minute. The suggested welding pressures are given in Table 22.10.

Table 22.10. Symalit MFA Hot Gas Welding Pressures.

	Welding Force, N (lbf)
For normal round section nozzles	10–15 (2.25–3.37)
For speed nozzles	~20 (4.5)

The welding speed should not exceed 7 cm/minute (2.8 inches/minute). The prepared weld and the welding rod should be cleaned with Frigen 113 before welding.

Reference: *The Welding of Symalit MFA Semi-finished Products*, Supplier guide, Symalit.

23 Ionomer

23.1 General

BASF AG: Lucalen I

Since they are thermoplastic, Lucalen moldings and film can be welded together by the application of heat and pressure. Examples of the techniques that can be adopted are vibration, ultrasonic, friction, hot gas, and hot plate welding.

Film can be heat sealed by slit-seal, thermal contact, and thermal impulse techniques. The main factors that govern the quality of the seam are temperature, pressure, and time.

Reference: *Lupolen, Lucalen Product Line, Properties, Processing*, Supplier design guide (B 581 e/(8127) 10.91), BASF Aktiengesellschaft, 1991.

23.2 Heat Sealing

BASF AG: Lucalen I

The ionomers can be heat sealed at temperatures about 20°C (36°F) lower than those required for polyethylene. In addition, they form dense seams because of their high hot tack. Another important property of the ionomers is that the presence of contaminants, for example, liquids, dust, fats, and oils, does not prevent them from being reliably heat sealed.

Reference: *Lupolen, Lucalen Product Line, Properties, Processing*, Supplier design guide (B 581 e/(8127) 10.91), BASF Aktiengesellschaft, 1991.

23.3 Adhesive Bonding

DuPont: Surlyn

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm), and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 23.1 give a good indication of the typical bond strengths that can be achieved as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually, as shown in Table 23.1, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 4011 and Super Bonder 414 instant adhesives, and Loctite 3105, a light cure adhesive, all created bonds which were stronger than the ionomer substrate. Flashcure 4305 light cure adhesive, Hysol E-00CL and E-30CL epoxy adhesives, and Hysol U-05FL urethane adhesive all achieved bond

Table 23.1. Shear Strengths of Surlyn Ionomer to Ionomer Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[a]

Material Composition	Loctite Adhesive					
	Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Grade 7940 4 rms	200 (1.4)	>1200[b] (>8.3)[b]	>1200[b] (>8.3)[b]	>1200[b] (>8.3)[b]	450 (3.1)	>1200[b] (>8.3)[b]
7940 roughened 68 rms	>1200[b] (>8.3)[b]	>1200[b] (>8.3)[b]	>1200[b] (>8.3)[b]	>1200[b] (>8.3)[b]	450 (3.1)	>1200[b] (>8.3)[b]
Grade 8940 4 rms	200 (1.4)	>1200[b] (>8.3)[b]	>1200[b] (>8.3)[b]	>1200[b] (>8.3)[b]	350 (2.4)	>1200[b] (>8.3)[b]
8940 roughened 68 rms	>1200[b] (>8.3)[b]	>1200[b] (>8.3)[b]	>1200[b] (>8.3)[b]	>1200[b] (>8.3)[b]	350 (2.4)	>1200[b] (>8.3)[b]
Grade 9950 4 rms	50 (0.3)	>1200[b] (>8.3)[b]	>1200[b] (>8.3)[b]	>1200[b] (>8.3)[b]	350 (2.4)	>1200[b] (>8.3)[b]
9950 roughened 68 rms	800 (5.5)	>1200[b] (>8.3)[b]	>1200[b] (>8.3)[b]	>1200[b] (>8.3)[b]	350 (2.4)	>1200[b] (>8.3)[b]

[a] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

[b] Due to the severe deformation of the block shear specimens, testing was stopped before the actual bond strength achieved by the adhesive could be determined (the adhesive bond never failed).

strengths comparable to the adhesives that achieved substrate failure. Speedbonder H3000 and H4500 structural adhesives both achieved the lowest bond strengths. There was no statistically significant difference between the bondability of the three grades of Surlyn evaluated, with the exception of the low bond strengths achieved by Black Max 380 on Surlyn 9950.

Surface Treatments: Surface roughening caused a large, statistically significant increase in the bond strengths achieved by Black Max 380 instant adhesive, but had no statistically significant effect with Depend 330 adhesive. The effect of Prism Primer 770 or 7701, and surface roughening with Prism 401, 4011 and Super Bonder 414 instant adhesives, or Loctite 3105 and 3311 light cure adhesives could not be determined, as with both the treated and untreated ionomer, the bonds created were stronger than the ionomer substrate.

Other Information: Ionomers can be stress cracked by uncured cyanoacrylate adhesives, so any excess adhesive should be removed from the surface immediately. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner and Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

23.4 Mechanical Fastening

DuPont: Surlyn

Molded-in Inserts: Surlyn has been successfully used with molded-in inserts in a number of applications, but thorough prototype testing should be carried out.

These points should be considered when designing for inserts:

- Inserts must be dry and free of oil, grease, and dirt.
- Inserts should not have sharp edges, and any knurling should have a rounded profile.
- To improve adhesion, metal inserts can be post heated to 260°C (500°F) by induction heating.
- Priming inserts can also improve adhesion.

Reference: *Surlyn Ionomer Resin Part and Mold Design Guide*, Supplier design guide (E-37240), DuPont.

24 Ketone-based Resins

24.1 Polyetheretherketone

24.1.1 General

Victrex: Aptiv (form: film)

Victrex have received several samples of Aptiv film which have been successfully welded using ultrasonic and laser methods.

Reference: *Heat Sealing, Welding & Laminating APTIV Film*, Supplier design guide, Victrex plc.

Victrex: Victrex PEEK

Victrex PEEK may be bonded using conventional thermoplastic welding techniques. However, these materials have exceptionally high melt temperatures, and considerable amounts of energy must be put into the polymer during welding to achieve a good bond. Satisfactory results have been obtained using hot plate, friction, and near-field ultrasonic welding.

Reference: *Victrex Processing Guide*, Supplier design guide (604/1.5M), Victrex plc, 2004.

24.1.2 Heated Tool Welding

Victrex: Victrex 450G

The PEEK plaques were dried for 3 hours in a vacuum oven at 150°C (302°F) prior to welding. Six welds were made using “optimum” conditions with a hot plate temperature of 400°C (752°F), six “cold” welds were made using a lower hot plate temperature of 350°C (662°F), and another six were made at 400°C (752°F) with the stops set incorrectly, so that there was no pressure during the welding cycle.

At normal welding pressures, when the hot plate temperature was decreased from 400°C (752°F) to 350°C (662°F), there was a trend for the crystallinity to increase from 32% to 34%, but there was no effect on the orientation.

Within the range of crystallinity and orientation observed, there was no effect on the mechanical properties.

The mean tensile and tensile-impact strengths of the normal pressure 400°C (752°F) welds were 91% and 62% of the parent material strengths, respectively. It was possible to obtain similar strengths at 350°C (662°F), but not consistently.

The mechanical properties of the low-pressure welds were poor, and affected by the presence of voids, which were produced at a hot plate temperature of 400°C (752°F), but not at 350°C (662°F), and were presumably due to material degradation.

Reference: Stevens SM: Structure property relationships in polyetheretherketone hot plate welds. ANTEC 1998, Conference proceedings, Society of Plastics Engineers, Atlanta, May 1998.

Victrex: Victrex 450G

Welding trials on PEEK were conducted on a hot plate welding machine. The approach rate between the test pieces and the hot plate was maintained at 0.2 m/s (7.9 inches/s) for all the welding trials. The depth of melt stops was fixed at 0.6 mm (0.024 inches). The following welding conditions were used:

- Heating pressure: 0.3 N/mm^2 (43.5 psi)
- Heating time: 90 seconds
- Plate temperature: 400°C (752°F)
- Welding pressure: 0.3 N/mm^2 (43.5 psi)
- Cooling time: 30 seconds

The results of the work showed that ageing in air at 250°C (482°F) resulted in more significant deterioration in tensile properties of PEEK welds than parent materials. The tensile and yield strength generally increased in both cases, whereas there was a reduction in elongation at break.

Ageing in boiling water for 21 days did not cause significant changes in tensile properties of either the PEEK welds or parent materials.

Fracture mechanic tests showed small changes in fracture toughness of PEEK parent material and welds after exposure in air at 250°C (482°F), and exposure to boiling water.

The maximum longitudinal residual stress measured in welded PEEK was 15 N/mm^2 (2200 psi), (in a specimen aged in air at ambient temperature for 5 months after welding). The maximum stress was reduced to 12 N/mm^2 (1700 psi) in a PEEK specimen aged for 12 months, but showed no further reductions in specimens aged for 21 and 28 months.

There was no further reduction of residual stress in PEEK specimens aged for up to 72 hours in boiling water. However, maximum residual stresses in PEEK specimens aged in air at 250°C (482°F) reduced to 9 N/mm^2 (1300 psi) after 8 hours and 0.2 N/mm^2 (30 psi) after 72 hours.

Reference: Tavakoli SM, Leggatt RH: Assessment of ageing properties and residual stresses in PEEK welds. ANTEC 1997, Conference proceedings, Society of Plastics Engineers, Toronto, May 1997.

24.1.3 Ultrasonic Welding

Victrex: Victrex PEEK 450G

Tests carried out on the near field ultrasonic welding of Victrex PEEK 450G to itself have shown that optimum results are obtained using a projection joint rather than a shear joint. With a high vibration amplitude (70 µm; 0.0028 inches) good weld strength can be obtained using 5 MPa (725 psi) weld pressure and a weld time of 1.0 seconds. Increasing the weld pressure above this level leads to an unacceptable amount of flash at the joint line. Far field ultrasonic welding is not suitable for Victrex PEEK.

Reference: *Victrex Polymers for Medical Applications*, Supplier technical report, ICI Advanced Materials.

PEEK (note: unidirectional; reinforcement: carbon fiber)

Ultrasonic welding of composites with thermoplastic-only energy directors produced excellent bonds. The short beam shear strength of the welded composites was equal to the short beam shear strength of compression molded parts. For PEEK composites (PEEK APC-2) as with other semicrystalline polymers, high-power inputs are necessary in order to heat the material to a temperature above the melting temperature. Therefore, attempts to weld the parts using 1:1, 1:1.5, and 1:2 boosters were generally not successful. However, using a 1:2.5 booster (amplitude 0.028 mm; 0.001 inches), pressures over 414 kPa (60 psi), and weld times greater than 4 seconds resulted in good welds. Control of the weld time is critical to the formation of strong bonds without distorting the parts.

Reference: Benatar A, Gutowski TG: Ultrasonic welding of thermoplastic components. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

24.1.4 Vibration Welding

Victrex: Victrex 450G

Vibration welds were made in PEEK using different pressures, with a variety of welding times, in order to produce welds with a range of mechanical properties. Welding times were between 2.5 and 15 seconds, welding pressure was between 1 and 5 Nmm^{-2} (145–725 psi), welding frequency was 200 Hz, vibration amplitude was 1.4 mm (0.055 inches), and the cooling time was 1.5 seconds.

Mechanical property results showed that welding pressures of 2 Nmm^{-2} (290 psi) or 3 Nmm^{-2} (435 psi) were necessary to produce satisfactory welds, and that (on the basis of tensile results) the optimum welding condition was 5 seconds at 3 Nmm^{-2} (435 psi), where the strengths were 92–95% of parent strength.

Mean weld crystallinities were 22–23% (8% lower than in the parent), and were unaffected by the welding time or welding pressure within the range observed.

At 2 Nmm^{-2} (290 psi), around 13% of the molecules in the crystalline phase were aligned parallel to the flow direction of the weld, and 11% at 3 Nmm^{-2} (435 psi). The amorphous phase orientation was about 2% lower than that of the crystalline phase.

The central weld region contained much smaller spherulites than the parent, and had therefore undergone a faster cooling rate, and was separated from the parent by a visible HAZ of deformed spherulites. The flow region also contained a central region which was similar to the weld and contained a centerline, and had therefore been fully molten and had undergone similar cooling conditions.

Failure generally occurred in the visible HAZ under tensile testing, and at the weld centerline in tensile impact tests.

Reference: Stevens SM: Structure/property relationships in polyetheretherketone vibration welds. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

24.1.5 Laser Welding

PEEK [form: 4 mm (0.157 inch) thick injection molded plaque]

Quasi-simultaneous welding involves a laser beam being guided over the length of the weld by means of a mirror system and scanning the joining surface several times over a relatively high speed (up to 10 m/s; 33 ft/s). This ensures a (quasi-) simultaneous and homogeneous heating and plasticization of the adherent surface, and makes it possible for press warped parts to be welded together during welding.

The joining surface was 35 × 4 mm (1.38 × 0.157 inches). The applied carbon black content for the absorbing part was 1.0 wt.%. The laser employed was a solid-state (Nd:YAG) laser with a wavelength of 1064 nm. The maximum power output of the laser in continuous-wave operation was approximately 250 W.

The highest weld strength (40.44 N/mm^2; 5865 psi) was predicted for the maximum intensity setting of 13 W/cm^2, a melting displacement of 0.7 mm (0.028 inches), and the lowest scanning velocity of 0.1 m/s (3.9 inches/s). The melting displacement of 0.7 mm (0.028 inches) permits such a flow of plasticized material that it is squeezed out of the joining zone, and thus ensures better mechanical and thermal homogenization of the weld seam. In addition to this, any thermally damaged material that may be present is transported out of the joining zone so that it is possible to increase weld strength. The strengthening effect of the squeeze flow seems to become less pronounced for melting displacements greater than 0.7 mm (0.028 inches).

Reference: Potente H, Fiegler G, Becker F, Korte J: Comparative investigations on quasi-simultaneous welding on the basis of the materials PEEK and PC. ANTEC 2002, Conference proceedings, Society of Plastics Engineers, San Francisco, May 2002.

24.1.6 Resistive Implant Welding

APC-2/AS4 (form: compression molded 16-layer unidirectional composite laminates; reinforcement: carbon fiber)

An experimental investigation on the resistance welding of APC-2/AS4 thermoplastic composite using a stainless steel mesh heating element was carried out. A ramped-voltage technique was adopted to join the samples in a single lap shear configuration. Experimental results indicated that the size of mesh had an effect on the weld strength. Samples welded using heating elements with a wire diameter of 0.04 mm (0.0016 inches), mesh thickness of 0.08 mm (0.0031 inches) and an open gap of 0.089 mm (0.0035 inches) gave weld strength values with 95% confidence of 49.01 MPa (7108 psi). The high weld strength could be attributed to the uniform temperature distribution across the weld, excellent impregnation of the heating element, creation of small inter-mechanical locks, and good polymer diffusion at the weld interfaces. The samples welded under the higher processing temperature of 450°C (842°F) exhibited the highest weld strength.

Reference: Yousefpour A: Resistance welding of thermoplastic composites using metal mesh heating elements. Joining Plastics 2006, Conference proceedings, London, UK, April 2006.

PEEK (form: 2 mm (0.079 inch) thick laminates; reinforcement: 50% carbon fiber)

The weldability of PEEK with PEI was examined and carbon fiber reinforced PEEK laminates were resistance-welded using a stainless steel mesh heating element.

Results showed that PEEK can heal when welded with PEI. The lap shear strength of PEEK/carbon fiber joints increased linearly with welding time, but reached a maximum value for a welding pressure between 0.3 and 0.5 MPa (43 and 72 psi) and constant welding time.

Reference: Yan J, Wang X, Qin M, Zhao X, Yang S: Resistance welding of carbon fibre reinforced polyetheretherketone composites using metal mesh and PEI film. *China Welding*, 13(1), p. 71, May 2004.

PEEK (form: lamination; reinforcement: carbon fiber)

Large-scale resistance welds were performed using different techniques: single-step (LSS) and multiple-step (LMS) welding. The former technique utilized a single heating element to weld the selected bond area as a one-step welding process. The latter technique utilized three separate heating elements, each covering one-third of the bond area, as part of a sequential welding process.

A joint overlap of 2.5 cm (1.0 inches) was selected to provide suitable lap shear specimens; the joint length was 30.5 cm (12.0 inches).

For the LSS heating element, 35.6 cm (14.0 inches) long and 2.5 cm (1.0 inches) wide, the power requirement was 42.8 V and 14.8 A. These parameters are equivalent to 633 W of power being placed into the bond interface region to soften and bond an amorphous PEI interlayer. A dwell temperature of 260°C (500°F) and a dwell time of 30 seconds were used with a constant pressure of 690 kPa (100 psi).

For the LMS heating element, 15.2 cm (6.0 inches) long and 10.2 cm (4.0 inches) wide, the power requirement was 18.3 V and 59.1 A, resulting in 1081 W of weld power. A dwell temperature of 260°C (500°F) and a dwell time of 30 seconds were used with a constant pressure of 690 kPa (100 psi). The first step was welded and allowed to cool below the glass transition temperature of the parent material (for PEEK, T_g ~143°C (289°F)) prior to sequencing to the next step. This procedure was repeated automatically for the second and third weld steps to complete welding of the entire joint.

Results showed that lap shear strengths achieved for large-scale welds agreed with earlier reported values for small-scale (coupon) welds. Higher weld uniformity was obtained with the LMS weld than the LSS weld. Higher lap shear strengths were obtained with the LMS weld than with the LSS weld. The heating element fiber orientation influenced weld uniformity and strength. Heating elements with fibers oriented transverse to specimen loading exhibited reduced strength. Uneven heating and overheating were minimized by reducing the heating element length within the bond region through use of the sequential resistance welding process.

Reference: McKnight SH, Holmes ST, Gillespie JW, Lambing CLT, Marinelli JM: Scaling issues in resistance-welded thermoplastic composite joints. *Advances in Polymer Technology*, 16(4), p. 279, 1997.

PEEK (form: lamination; reinforcement: carbon fiber)

The feasibility of using the resistance heated fusion bonding process to produce high quality joints between 7075-T6 aluminum alloy and carbon fiber (IM-7)/PEEK laminates with a glass (S-2)/PEEK coated heating element was demonstrated. The C-scans and optical micrographs of the joint appeared uniform throughout the majority of the bond regions, which indicated that high-quality fusion bonds are achievable. Lap shear strengths approaching 20 MPa (2900 psi) were obtained, with process times from start to completion of several minutes.

Definite trends between processing parameters, such as dwell time and applied pressure, and joint quality and performance were observed.

The high thermal conductivity of the aluminum creates large temperature gradients along the bond area, which may be detrimental to the final joint quality and performance.

The failure of the joints often occurred at the metal foil glass/PEEK interface. Thus, techniques must be developed to improve the adhesion of the foil to the thermoplastic polymer. Furthermore, overheating at the exposed portions of the heating element must be controlled. This can be accomplished with active cooling, or through the use of an embedded heating element connection.

Reference: McKnight SH, Holmes ST, Gillespie JW, Lambing CLT, Marinelli JM: Resistance heated fusion bonding of carbon fiber/PEEK composites and 7075-T6 aluminum. ANTEC 1993, Conference proceedings, Society of Plastics Engineers, New Orleans, May 1993.

24.1.7 Heat Sealing

Victrex: Aptiv (form: film)

Two layers of Aptiv film may need to be heat sealed for the production of a bag, or providing the encapsulation of electronic devices, for example. As Victrex PEEK is a thermoplastic material, heat sealing can be easily accomplished by heating the film to the melt point, and applying pressure to bring the molten polymer into intimate contact. A typical process temperature of about 340–370°C (644–698°F) can be used, depending on equipment. A contact time of a few seconds is required to allow the two melt surfaces to contact and intimately bond. The applied pressure will vary according to the thickness of the film and equipment. If excessive flow and thinning of the heat sealed section occurs, then it is likely that too much pressure has been applied.

Reference: *Heat Sealing, Welding & Laminating APTIV Film*, Supplier design guide, Victrex plc.

24.1.8 Adhesive Bonding

PEEK

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 24.1 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and addi-

Table 24.1. Shear Strengths of PEEK to PEEK Adhesive Bonds Made Using Adhesives Available from Loctite Corporation*

Material Composition		**Loctite Adhesive**					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/Prism Primer 770**	**Super Bonder 414** (Instant Adhesive General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Victrex 450G control	Unfilled resin courtesy of Victrex, USA 4 rms	150 (1.0)	250 (1.7)	250 (1.7)	200 (1.4)	350 (2.4)	1100 (7.6)
450G roughened	22 rms	700 (4.8)	350 (2.4)	350 (2.4)	300 (2.1)	350 (2.4)	1100 (7.6)
PEEK 450 CA30	30% carbon fiber courtesy of Victrex, USA	150 (1.0)	200 (1.4)	450 (3.1)	250 (1.7)	450 (3.1)	950 (6.6)
Thermocomp LF-1006	30% glass fiber courtesy of LNP Engineering Plastics	100 (0.7)	250 (1.7)	550 (3.8)	400 (2.8)	500 (3.5)	1200 (8.3)
Lubricomp LCL-4033 EM	15% carbon fiber, 15% PTFE courtesy of LNP Engineering Plastics	100 (0.7)	400 (2.8)	300 (2.1)	250 (1.7)	500 (3.5)	900 (6.2)

*All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

tives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 24.1 so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in “real-world” applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Loctite 3105 and Flashcure 4305 light cure adhesives consistently achieved the highest bond strengths on PEEK. With the exception of hot melt adhesives, all other adhesives developed moderate to good bond strength on unfilled PEEK.

Surface Treatments: Surface roughening caused either no effect, or a statistically significant increase in the bond strengths achieved on PEEK. Prism Primer 770, used in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, had no overall statistically significant effect on the bondability of PEEK. However, Prism Primer 770 and 7701 did result in a statistically significant increase in the bond strengths achieved on the PEEK 450 CA 30 and Thermocomp LF-1006 grades.

Other Information: PEEK is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

Invibio: PEEK Optima LT1 (form: injection molded plaque)

Two types of adhesive (acrylic and epoxy) were selected for adhesive bonding trials. The effects of a range of bonding parameters on the lap shear strength of the joints were evaluated. These parameters included surface modification either by grit blasting (with NK60 grit) or by Nd:YAG laser treatment or by the application of a suitable primer (Loctite 7701).

The highest mean lap shear strength (6.2 MPa; 899 psi) bonded with a one-part cyanoacrylate adhesive (Loctite 4061) was achieved after grit blasting with NK60. The mean lap shear strength of untreated samples was only 1 MPa (145 psi).

PEEK adherends treated with a Nd:YAG laser at 355 nm and 532 nm, at treatment speeds of 10, 20, and 100 mm/minute (0.4, 0.8 and 3.9 inches/minute), bonded with Loctite 4061 adhesive all provided joints with failure occurring cohesively within the PEEK. The lap shear strength for these samples varied from 3.7 to 4.6 MPa (537–667 psi).

For PEEK adherends bonded with EPO-TEK 301-2 (from Epoxy Technology) and Loctite Hysol M-31CL two-part epoxy adhesives, grit blasting gave mean lap shear strengths of 4.6 MPa (667 psi) and 4.3 MPa (624 psi), respectively. All these joints showed a mixed failure of adhesive at the interface and cohesive within the adhesive. The control joints for these two adhesives gave mean lap shear strengths of 1.3 MPa (189 psi) and 1.7 MPa (247 psi), respectively, with all joints failing at the interfacial regions.

The acrylic adhesives used after grit blasting gave a mean lap shear strength of 5.9 MPa (856 psi) for Loctite 4061 and 4.7 MPa (682 psi) for Loctite 4305 (one-part UV cure). The control joints gave mean lap shear strengths of only 1.0 MPa (145 psi) and 1.7 MPa (247 psi), respectively. Again, all joints prepared after grit blasting showed a mixed failure of adhesive at the interface and cohesive within the adhesive. The control joints all failed at the interface.

Reference: Tavakoli M, Green S, Cartwright K, Mycock S: Joining of polyetheretherketone (PEEK) for short and long term implantable medical device applications. Medical Polymers 2004, Conference proceedings, Dublin, Ireland, November 2004.

Table 24.2. Bond Strengths of Various Adhesives with Victrex PEEK-based Materials

Adhesive	Type	Manufacturer	Failure stress, MPa (psi)			
			23°C (73°F)	**120°C (248°F)**	**150°C (302°F)**	**200°C (392°F)**
S-4215 RA	Acrylic tape	ATP Adhesive Systems	0.2 (29) CF	0.03 (4.3) CF		
Araldite AV138M + HV 998	Epoxy	Huntsman	5.5 (800) IF+CF	3.4 (500) CF		
Araldite AV 119	Epoxy	Huntsman	41.8 (6000) SF	4 (575) CF	1.5 (225) IF+CF	
HAF 8401	Nitrile rubber phenolic resin	Tesa AG	47.3 (6850) SF	2.4 (350) IF	1.9 (275) IF	
Duralco 4460	Epoxy	Cotronics Corp.	1.7 (250) ICF	–	0.5 (75) CF	0.4 (58) IF+CF
Duralco 4703	Epoxy	Cotronics Corp.	16.7 (2400) SF	–	3.4 (500) CF	1 (145) CF
EPO-TEK 353 ND	Epoxy	Epoxy Technology	36.2 (5250) SF	–	3.1 (450) CF	1 (145) IF+CF
Duralco 4525	Epoxy	Cotronics Corp.	3.3 (475) CF	–	–	0.6 (87) CF

IF: adhesive failure at the adhesive/substrate interface; CF: cohesive failure of the adhesive, leaving adhesive on both sides of the substrate; SF: the adhesive is of sufficient strength to cause failure within the Victrex PEEK substrate; ICF: mixed mode failure with fracture propagation switching between interfacial and cohesive failure.

Victrex: Victrex PEEK

Most adhesive types are compatible with Victrex PEEK-based materials. Epoxy, cyanoacrylate, anaerobic, and silicone adhesives have been shown to successfully bond Victrex PEEK. A list of typical adhesives and their corresponding bond strengths is shown in Table 24.2.

There are a variety of surface treatments available which increase the strength of adhesive bonds made with Victrex PEEK. A comparison of bond strengths achieved using the most common of these techniques is given in Table 24.3. For these measurements Victrex 450G samples were bonded together in a single overlap shear geometry with a two-component epoxy from Ciba (AV138M/HV998), and using a 15 minute 100°C (212°F) curing cycle.

Reference: *Victrex Processing Guide,* Supplier design guide (604/1.5M), Victrex plc, 2004.

PEEK (form: composite)

For PEEK adherends, plasma treatment can result in substantial increases in peel strength and, most importantly, a transfer of the locus of failure away from the adhesive-PEEK interface to within either the adhesive layer or the PEEK adherend.

Reference: Millington S, Shaw SJ: Surface treatment approaches for polymer composites. The Joining of Plastics and Polymer Composite Materials, IMechE seminar proceedings, Cambridge, UK, October 2002.

Victrex: Victrex 450G (form: unreinforced); APC-2 (reinforcement: carbon fiber)

The adhesives used in this study were: PLUS CP792 (a cyanoacrylate by Permabond), Araldite AW106 + HV953V hardener (two-part epoxy by Ciba Speciality Chemicals) and AF163-2K (a modified epoxy film by 3M).

Trials were performed using three excimer lasers: XeCl (wavelength 308 nm), ArF (wavelength 193 nm) and KrF (wavelength 248 nm). The pulse energy of the XeCl laser was 120 mJ and, for both ArF and KrF lasers, it was 100 mJ, with a pulse duration of 10–15 ns. The beams were focused through a 500 mm (19.7 inch) focal length mirror to produce a rectangular area of 6 × 3 mm (0.24 × 0.12 inches) on the adherend. For each specimen, a treated width of approximately 25 mm (1 inch) was produced.

Results of this work have shown that the excimer lasers were all very effective in significantly increasing the joint strength of PEEK bonded with the cyanoacrylate adhesive. XeCl and KrF lasers provided the highest joint strength at 2 Hz (mean lap shear strengths of 4.08 MPa (592 psi) and 4.78 MPa (693 psi), respectively), whereas the ArF laser gave the highest values of mean lap shear strength at 25 Hz (5.17 MPa; 750 psi). Most of these joints failed within the adherend.

For APC-2 joints bonded with the AF163 epoxy adhesive, the ArF laser treatment at 25 Hz provided the joints with the highest percentage of failure (57%) within the adherend. The KrF laser was also effective when used at 5 Hz.

Laser-treated PEEK and APC-2 joints, exposed at 50°C (122°F) and 96% RH for several weeks, showed excellent resistance to ageing. PEEK joints exposed to 1750 hours and APC-2 joints to 2060 hours under these conditions showed no loss in strength.

Reference: Tavakoli SM, Riches ST: Laser surface modification of polymers to enhance adhesion. Part II—PEEK, APC-2, LCP and PA. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

Table 24.3. Comparison of Surface Preparation Techniques for Adhesive Bonds to Victrex 450G

	Bond strength, MPa (psi)
Untreated	0.7 (102)
Roughening	2.1 (305)
Acid etch	5.5 (798)
Excimer laser	5.6 (812)
UV lamp	5.0 (730)
Plasma chamber	5.0 (722)

Victrex: Victrex PEEK

Many adhesive types can be used for bonding Victrex PEEK either to itself or to other materials. The bond strength will be very dependent on the surface preparation prior to bonding.

Adhesive Types: Epoxy, cyanoacrylate, anaerobic and silicone adhesives will all bond Victrex PEEK. The epoxy adhesives, however, give by far the strongest bond. No stress cracking problems have been encountered.

Surface Preparation: Surfaces to be bonded must be clean, dry, and free from grease. Genklene solvent may be used to degrease the surface. More aggressive surface activation procedures such as surface roughening, flame treatment, or etching with chromic acid may help to increase bond strengths. Using a general purpose Araldite 100 epoxy adhesive, flame oxidation improves bond strength by 20% over degreased surfaces and chromic acid etching improves bond strength by about 30% over degreased surface bond strengths.

Reference: *Victrex Polymers for Medical Applications*, Supplier technical report, ICI Advanced Materials.

24.2 Polyetherketoneetherketoneketone

24.2.1 General

BASF AG: Ultrapek

Ultrapek can be welded by heated tool, vibration, spin, and ultrasonic techniques. High frequency welding is not feasible, owing to Ultrapek's low dissipation factor. Hot air welding is mostly manual and is primarily resorted to for assembling individual parts or for short production runs. A point to note in all welding techniques is that the parts to be assembled must be dry.

Reference: *Ultrapek Product Line, Properties, Processing*, Supplier design guide (B 607 e/10.92), BASF Aktiengesellschaft, 1992.

24.2.2 Heated Tool Welding

BASF AG: Ultrapek

Heated tool welding is mainly resorted to for assembling large parts, for example, tubes and sheet. Ultrapek demands high heated tool temperatures, for which conventional nonstick coatings are unsuitable.

In thermal contact processes, the heated tools must be continuously freed from adhering residues, and preference should therefore always be given to contactless heating by thermal radiation. The distance between the joint to be welded and the hot plate should be about 0.2–0.6 mm (0.008–0.024 inches). In view of the high welding temperatures that are required, the switchover time must be very short—if possible, less than one second—in order to avoid the surface of the melt cooling below the solidification point.

Particularly good results have been obtained with the following welding parameters:

- heated tool temperature: 400–500°C (752–932°F) (contact)
- heating-up period: 10–90 seconds
- pressure: 0.5–5 MPa (72–725 psi)

Reference: *Ultrapek Product Line, Properties, Processing*, Supplier design guide (B 607 e/10.92), BASF Aktiengesellschaft, 1992.

24.2.3 Ultrasonic Welding

BASF AG: Ultrapek

By virtue of their versatility, ultrasonic welding techniques can be economically and synchronously integrated in automatic units for injection moldings produced in large runs. It is primarily suitable for small parts with cross-sectional areas of up to 200 cm^2 (31 $inch^2$) or for welds of up to 10 cm^2 (1.55 $inch^2$) in area. Two or more welding operations must be performed simultaneously or consecutively if the parts are larger. Less than two seconds is necessary for welding, with the result that extremely short cycle times are feasible. The geometry of the seams must be designed to accommodate the exigencies of ultrasonic welding. The parameters that have to be set depend on the design of the part and the nature of the material, and should be optimized by trial and error.

Typical welding parameters for a 20 kHz installation are:

- amplitude: 40–60 μm
- welding time: 0.3–0.8 seconds
- pressure: 0.5–5 MPa (72–725 psi)

Reference: *Ultrapek Product Line, Properties, Processing*, Supplier design guide (B 607 e/10.92), BASF Aktiengesellschaft, 1992.

24.2.4 Vibration Welding

BASF AG: Ultrapek

Friction or vibration welding is resorted to for joining extensive surfaces that lie in one plane or are, at the most, curved in only one direction. The seam must be designed so that there is sufficient room for movement in the direction of vibration. The amplitude at which the surfaces to be bonded should be heated depends on the frequency of the machine, that is:

- 1.0–4.0 mm (0.04–0.16 inches) for 100 Hz
- 0.5–2.0 mm (0.02–0.08 inches) for 240 Hz.

About 2–10 seconds are required for welding, and the pressure is about 0.5–2 MPa (72–290 psi).

Reference: *Ultrapek Product Line, Properties, Processing*, Supplier design guide (B 607 e/10.92), BASF Aktiengesellschaft, 1992.

24.2.5 Hot Gas Welding

BASF AG: Ultrapek

Hot air welding is suitable for assembling large or complicated parts. The air temperature should be between 450°C (842°F) and 500°C (932°F), and the diameter of the filler rod should correspond to the thickness of the parts to be welded together.

Reference: *Ultrapek Product Line, Properties, Processing*, Supplier design guide (B 607 e/10.92), BASF Aktiengesellschaft, 1992.

24.2.6 Adhesive Bonding

BASF AG: Ultrapek

The adhesives used for bonding Ultrapek articles to other articles produced from Ultrapek or another material may be based on epoxy resins, cyanoacrylates, polyurethanes, silicones, or other polymers. The strength of the bond depends considerably on the pretreatment given to the adherends. Best results are achieved by roughening the surfaces and degreasing them with a solvent. Examples of other techniques for increasing the bond strength are plasma treatment or etching with potassium dichromate/sulfuric acid solution. Environmental stress cracking problems do not arise.

Reference: *Ultrapek Product Line, Properties, Processing*, Supplier design guide (B 607 e/10.92), BASF Aktiengesellschaft, 1992.

24.2.7 Mechanical Fastening

BASF AG: Ultrapek

Riveting and Beading: Ultrapek parts can be held together by threaded and—with certain reservations—snap-on connectors. If threaded connections are subjected to heavy loads and have to be frequently unscrewed and remade, threaded metal inserts can be accommodated in recesses formed for that purpose in the Ultrapek molding. The inserts are heated and pressed into the recesses or, preferably, embedded by ultrasonic techniques. Sleeves, bushings, bolts, and other metal parts can be secured by ultrasonic welding machines.

Indissoluble bonds between Ultrapek parts and other materials, for example, sheet metal, can be very easily formed by incorporating rivet shanks in the moldings. After the metal part has been inserted on the shank, the heads are formed by ultrasonic means with the aid of a special tool.

In beading, the projecting Ultrapek material is also plasticized by ultrasonic means and formed so that metal or other parts can be enclosed.

Reference: *Ultrapek Product Line, Properties, Processing*, Supplier design guide (B 607 e/10.92), BASF Aktiengesellschaft, 1992.

24.3 Polyetherketone

24.3.1 General

Victrex: Victrex PEK

Victrex PEK can be welded to itself using conventional ultrasonic and friction welding techniques. When using these techniques, it should be borne in mind that because Victrex PEK has a higher melting point than most polymers, considerable amounts of energy must be put into the polymer during welding to achieve a good bond.

Reference: *Victrex PEK Properties and Processing*, Supplier design guide (VP2/October 1987), ICI Advanced Materials, 1987.

24.3.2 Adhesive Bonding

Victrex: Victrex PEK

Many types of adhesive can be used for bonding Victrex PEK either to itself or to other materials. The bond strength will be very dependent on the surface preparation prior to bonding.

Surface Preparation: Surfaces to be bonded must be clean, dry, and free from grease. Genklene (1,1,1-trichloroethane) or a similar degreasing solvent may be used to degrease the surface. More aggressive surface activation procedures such as surface roughening, flame treatment, plasma etching (especially in argon), or chromic acid etching may help to increase bond strengths. Using a general purpose Araldite 100 epoxy adhesive, flame oxidation improves the bond strength by 20% and chromic acid etching by about 30% over the bond strengths of degreased surfaces.

Adhesive Types: Epoxy, cyanoacrylate, anaerobic, and silicone adhesives will all bond Victrex PEK. The epoxy adhesives, however, give by far the strongest bond. In all cases, the relevant adhesive manufacturer should be consulted to ensure that the optimum bonding techniques and the most appropriate adhesive are being used.

Reference: *Victrex PEK Properties and Processing*, Supplier design guide (VP2/October 1987), ICI Advanced Materials, 1987.

24.4 Polyetherketoneketone

24.4.1 Adhesive Bonding

PEKK (form: laminate; reinforcement: graphite fiber)

The specimens used in this investigation were long discontinuous fiber (LDF) AS4/PEKK composite laminates. The surfaces were either grit-blast or corona-treated prior to bonding. An adhesive per Boeing Material Specification D210-12065 (equivalent to American Cyanamid FM-300) was used, and was cured at 350°F (177°C) for 2 hours at 85 psi (0.59 MPa) pressure.

All the bonded joints evaluated gave comparable static strengths. No significant loss in strength was observed for joints exposed to moisture for 30 days. The fatigue behavior of the bonded joints showed the endurance limit occurring between 20 and 30% of their static ultimate strengths. Additionally, significant reduction in stiffness was observed prior to failure. The stiffness reduction was observed to be stress level dependent, with lower stress levels experiencing greater stiffness loss. Significant loss in strength was also observed for specimens that survived one million fatigue cycles.

Reference: Whitworth HA: Fatigue evaluation of composite bolted and bonded joints. *Journal of Advanced Materials*, 30(2), p. 25, 1998.

24.4.2 Mechanical Fastening

PEKK (form: laminate; reinforcement: graphite fiber)

The specimens used in this investigation were long discontinuous fiber (LDF) AS4/PEKK composite laminates. Two different fastener types were employed: titanium fasteners and IM7/PEEK graphite composite fasteners. The mechanically fastened joints were made from quasi-isotropic (45°/0°–45°/90°) laminates to avoid the shear-out problems resulting from holes drilled in unidirectional laminates.

Static and fatigue tests were conducted on two different bolt clamp-up levels. While no significant change in static strength with clamp-up was observed, clamp-up did have a significant effect on the fatigue performance. The titanium fasteners showed slightly better fatigue performance than the thermoplastic fasteners with equal clamp-up loads, while the fully torqued titanium fastener joints had significantly improved fatigue performance. Significant hole elongation was also observed during tensile fatigue testing of these laminates.

Reference: Whitworth HA: Fatigue evaluation of composite bolted and bonded joints. *Journal of Advanced Materials*, 30(2), p. 25, 1998.

24.5 Polyketone

24.5.1 Laser Welding

Shell: Carilon

The laser diodes used had output capabilities between 5 and 60 W/cm with a wavelength output of 800–900 nm.

During the welding of PK, any moisture present in the material produced a vapor pressure dependent on the temperature of the melt. If the vapor pressure exceeded the clamp pressure of the welding process, porosity would form if the temperature was maintained for a sufficient time. Thus, one important fact that was seen in this study was that once the cycle time was reduced to 3–4 seconds, sample drying was not required to eliminate porosity.

The results of this study showed that polyketone can be welded with TTIR with weld strengths of 98% of parent material, using a power density of 40 W/cm. Thicknesses above 8 mm (0.315 inches) will be difficult to weld with TTIR (wavelengths between 800 and 900 nm) due to surface heating and power requirements (45 W/cm), a transparent pressure foot may help remove heat and reduce marking.

Various grades of Carilon can be welded in all possible combinations, but to achieve maximum weld strength, similar grades should be welded.

Reference: Grewell DA, Nijenhuis W: TTIR welding of aliphatic polyketone. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

25 Polyamides

25.1 Nylon General

25.1.1 General

EMS-Chemie: Grilon, Grivory

Very good weld joints can be obtained for shaped parts made of Grilon and Grivory using heated element welding, ultrasonic welding, infrared welding, laser welding and vibration welding technology. The best results are achieved using ultrasonic welding. Vibration welding offers the possibility of welding amorphous and glass-reinforced Grivory.

Parts made of Grivory can be fastened well with self-tapping screws. Metric threads can be integrated directly into components.

References: *Grilon: The Traditional Product*, Supplier design guide, EMS-Chemie.

Grivory G Partially Aromatic Polyamides, Supplier design guide, EMS-Chemie.

BASF: Ultramid

Practically all methods developed for welding thermoplastics are suitable for Ultramid. The following welding methods are employed for moldings: ultrasonic, heating-element (thermal sealing, radiation welding), vibration (linear, biaxial), spin welding and laser beam welding. The newly developed Ultramid A3WG6 LT black 23229 provides the user with a highly developed product for laser welding applications.

Heat impulse and high frequency welding, in the case of suitable formulations, are preferably used for film. However, laser beam, heating-element and ultrasonic welding may also be used.

Reference: *The Processing of BASF Polyamides*, Supplier design guide, BASF Corporation.

BIP Chemicals: Beetle

Nylon can be welded by all the processes normally employed for thermoplastics, such as friction welding and ultrasonic welding. The components should be dry prior to welding, since excessive moisture can reduce the strength of the bond.

Reference: *Beetle & Jonylon Engineering Thermoplastics*, Supplier marketing literature (BJ2/1291/SP/5), BIP Chemicals Limited, 1991.

25.1.2 Heated Tool Welding

Nylon

Under optimum conditions, a strength of 58% of parent and a strain at failure of 1.9% can be achieved in polyamide welds made by the hot tool welding process.

Reference: Stokes VK: Toward a weld-strength database for hot-tool welding of thermoplastics. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

Nylon (form: random long fiber glass matt)

In nylon reinforced with random glass matt (GMT), the fibers are ineffective for reinforcing hot-tool butt welds. The maximum weld strengths attained with GMT are comparable to the strengths of good welds of the unfilled material. The optimum hot-tool welding parameters for the reinforced materials are different from those for the unfilled material.

Reference: Gehde M, Giese M, Ehrenstein GW: Welding of thermoplastics reinforced with random glass matt. *Polymer Engineering and Science*, 37(4), p. 702, April 1997.

25.1.3 Ultrasonic Welding

DuPont: Zytel

Parts of glass reinforced Zytel nylon can be ultrasonically welded; sometimes with greater ease than the unreinforced material. Resins in the Zytel nylon 79G, 70G series may be welded with weld strengths equal only to that of the base unreinforced material because no glass reinforcement occurs at the weld. For this reason, if the strength of the joint weld is required to equal that of the reinforced resin, the joint area must be increased in relation to the wall thickness. This can be easily done with the shear joint. Of the glass reinforced Zytel resins, Zytel 79G13 is the most difficult to weld.

At the 13% glass reinforcement level, excessive marring and flashing under the welding horn may still occur.

Nylon resins absorb somewhat more moisture from the air after molding than most other plastics. When released from joint surfaces during welding, moisture causes poor weld quality. For best results, parts of Zytel should either be ultrasonically welded immediately after molding or kept in a dry as-molded condition prior to welding. Exposure of 1 or 2 days to 50% relative humidity at 23°C (73°F) is sufficient to degrade weld quality by 50% or more. Welding parts at longer than normal weld times may offset this loss of weld quality, but often at the expense of heavy weld flash and marring under the welding horn. The part temperature near the horn approaches that at the joint during welding, and therefore lengthening weld cycles may cause severe problems.

Parts may be kept dry for periods up to several weeks by sealing them in polyethylene bags immediately after molding. For longer periods, greater protective measures must be taken such as the use of jars, cans, or heat sealable moisture barrier bags. Parts that have absorbed moisture may be dried prior to welding in a drying oven.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I*, Supplier design guide, DuPont Company, 2002.

DuPont: Zytel

With welding equipment set at conditions that produce quality welds in unpigmented parts, the quality of welds in pigmented parts may be markedly lower reflected in welds of lower strength and greater brittleness. The presence of pigments appears to influence the means of heat generation at the joint. Often lower weld quality may be offset by welding pigmented parts at longer weld times than for unpigmented parts. However, these longer weld times may produce undesirable effects such as the formation of excess weld flash and marring under the welding horn. Use of dye coloring systems, which do not significantly affect ultrasonic welding, may offer an alternative solution.

The adverse effects on ultrasonic weldability caused by pigments also apply to the welding of materials with externally or internally compounded lubricants and mold release agents. Relatively small quantities of such materials appear to adversely affect the means of heat generation in the joint during welding. If spray-on mold release agents are used in molding of otherwise unlubricated molding material, these parts should be thoroughly cleaned prior to welding.

Reference: *Ultrasonic Welding of Delrin Acetal Resin, Zytel Nylon Resin, Lucite Acrylic Resin*, Supplier technical report (171), DuPont Company, 1972.

Nylon

The relationship of ultrasonic weld strength to weld/hold force was studied. It is seen that weld strength is generally inversely proportional to weld force. High weld force promotes strong molecular alignment and results in weaker welds. At the lower weld forces (<455 N; 102 lbf) this relationship does not hold true due to sample warpage. By varying the force during the weld cycle it was found that both short cycle times and strong welds could be achieved simultaneously. Force profiling results in maximized weld strengths while the weld time was decreased by 28% for polyamide. In polyamide there is also a significant increase in strength, from 24 to 41 MPa (3480–5950 psi), a 71% increase. Micrographs of the weld zone revealed that the increase is due to an increase in weld area resulting from the energy director being driven into the bottom part during the high force stage of the welding cycle.

Reference: Grewell DA: Amplitude and force profiling: studies in ultrasonic welding of thermoplastics. ANTEC 1996, Conference proceedings, Society of Plastics Engineers, Indianapolis, May 1996.

Nylon

Ultrasonic welding is a very complex process that is difficult to control, especially for semicrystalline polymers. Two approaches for improving control of ultrasonic welding were investigated—power threshold control and closed-loop power tracking. Power threshold control relies on the rapid rise in power which is observed near the end of welding for triggering a shutoff of the ultrasonic vibration. For closed-loop power tracking of a preset power curve, the amplitude of vibration is varied in real time in order to impose a power curve that is known experimentally to produce good joints. For polyamide, these two approaches were superior to the energy mode, displacement mode, and time mode in producing strong joints with low standard deviations.

Reference: He F: Effect of amplitude and pressure control on the strength of ultrasonically welded thermoplastics.

ANTEC 1996, Conference proceedings, Society of Plastics Engineers, Indianapolis, May 1996.

25.1.4 Vibration Welding

DuPont: Zytel

Vibration welding is suitable for all grades of Zytel nylon resins. No special care has to be taken concerning water absorption before welding, provided that the parts are stored at a relative humidity no higher than 50%. Butt joints of parts in unreinforced polyamide are usually stronger than the part itself. Fillers and glass fibers reduce joint strength depending on their quantity. Thus, 30% glass fibers cause a reduction of up to 50% in strength. Parts in this resin must be designed very carefully.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I*, Supplier design guide, DuPont Company, 2002.

Nylon (form: random long fiber glass matt)

In nylon reinforced with random glass matt (GMT), the fibers are ineffective for reinforcing vibration-welded butt joints. The maximum weld strengths attained with GMT are comparable to the strengths of good welds of the unfilled material. High welding pressures and high amplitudes result in lower mechanical properties. The optimum penetration depends on the fiber content of the bulk material. This penetration dependence is different from that for unfilled thermoplastic, for which the mechanical properties are independent of the penetration once a steady state has been attained.

Reference: Gehde M, Giese M, Ehrenstein GW: Welding of thermoplastics reinforced with random glass matt. *Polymer Engineering and Science*, 37(4), p. 702, April 1997.

Nylon

The mechanical properties of molded polyamide parts are determined to a large extent by the moisture content of the material. In the vibration welding process, the formation of bubbles in the joining zone is something that is readily evident. Opinions differ greatly regarding the development and prevention of these bubbles, as well as their influence on weld strength.

This study draws the following conclusions regarding the welding of hygroscopic polyamides:

- A high joining pressure prevents the formation of vapor bubbles in the weld.
- Bubble formation cannot be entirely prevented in the weld upset. Even if there is only a low residual moisture content in the parts to be welded, the pressure reduction that occurs when the hot melt escapes into the weld upset causes water vapor to form.
- Weld strength cannot be increased through predrying, since values equivalent to those of the base material are already being attained. The greater rigidity of the molded parts and the lower level of energy required to melt predried or freshly molded parts do, however, reduce the amount of welding time required and lead to a weld upset that contains fewer bubbles.

Reference: Potente H, Uebbing M: The effects of moisture on the vibration welding of polyamide. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

DuPont: Zytel (material composition: 30% glass-fiber reinforcement)

The study was undertaken to compare nylon 66 and nylon 6 when vibration welded. Unwelded nylon 66 has a higher tensile strength than nylon 6 (65 versus 50 MPa (9430 versus 7250 psi) when tested in the moist state). The maximum service temperature of nylon 66 is also higher than that of nylon 6 (typically 241°C (466°F) versus 199°C (390°F)). Vibration welds made in nylon 66 give higher weld strengths than nylon 6 when tested at elevated temperature regardless of material condition, orientation or displacement.

Welding nylon 6 and nylon 66 in a 50% RH-conditioned state significantly reduces the weld strength at 23°C (73°F) when compared to material in the dry as molded state. Nylon 66 gives weld strengths up to 10 MPa (1450 psi) higher than nylon 6 when welded in the conditioned state.

When tested at 23°C (73°F), welds made in the longitudinal direction gave weld strengths up to 20% higher than welds made in the transverse direction. At 120°C (248°F), welds made in the dry as molded state were not affected by material vibration direction. In both directions, nylon 66 gave higher weld strengths than nylon 6.

Increasing the testing temperature of the tensile test decreases the strength of welds made in nylon 6 and nylon 66. Nylon 66 gives up to 28% stronger welds at 120°C (248°F) than nylon 6.

In order to achieve an optimum weld time, displacement of the weld material during the weld cycle must be kept to a minimum without affecting the quality of the weld. Increasing material displacement above 1 mm (0.039 inches) through prolonged weld times does not increase the strength of the weld, but produces excessive flash.

Increasing weld pressure gives lower failure strengths in both nylon 6 and nylon 66. At the higher weld pressures, the final stresses in the material would be expected to be higher, resulting in a decrease in the tensile strength of the joint. At lower pressures, the reverse is true, but lower pressures lead to longer weld times. This has been compensated for by equipment manufacturers by the introduction of welding machines that allow pressure profiling.

Reference: Froment ID: Vibration welding nylon 6 and nylon 66—a comparative study. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

25.1.5 Spin Welding

DuPont: Zytel

As a first approximation, the peripheral welding speed for Zytel should be chosen between 3 and 5 m/s (120–200 inches/s). Then the pressure must be adjusted until the desired result is obtained in a welding time of 2–3 seconds.

Reference: *DuPont Engineering Polymers. General Design Principles—Module* I, Supplier design guide, DuPont Company, 2002.

25.1.6 Laser Welding

Nylon (reinforcement: 30% glass fiber)

This work reviews the results of welding experiments using a box geometry with a three-dimensional weld line. The laser source was a diode laser with a wavelength of 940 nm. The focus dimensions of the laser beam were 1.5 × 1.5 mm (0.06 × 0.06 inches). The laser head was fixed to an extension arm of a 6-axis robot. An analysis of the welding process was completed using standardized design of experiments. The parameters that were studied were laser power, velocity of the laser, and welding pressure. The lower, absorbing layer contained <0.25 wt.% carbon black.

With laser velocities ranging from 50 to 100 mm/s (2–4 inches/s), weld line lengths of approximately 240 mm (9.5 inches) were possible with welding times between 2.4 and 4.8 seconds. Compared to heated tool welding, this is a relatively short cycle time. Over a relatively wide range of energy densities (0.7–1.4 J/mm^2) hermetic welding was produced.

Reference: Haberstroh E, Luetzeler R: 3-D laser transmission welding. ANTEC 2003, Conference proceedings, Society of Plastics Engineers, Nashville, May 2003.

BASF: Ultramid

Suitable Ultramid combinations for laser welding are given in Table 25.1.

Reference: *Transmission Laser-Welding of Thermoplastics*, Technical Information (WIS 0003 e 01.2001), BASF Aktiengesellschaft, 2001.

25.1.7 Solvent Welding

EMS-Chemie: Grilon

Grilon's excellent resistance to chemicals makes it a difficult material to bond.

Solvents based on phenol (resorcinol, cresol) are particularly suited for bonding Grilon.

Reference: *Grilon: The Traditional Product*, Supplier design guide, EMS-Chemie.

Table 25.1. Ultramid Product Combinations Suitable for Laser Welding

Transmitting component	Absorbing Component
A3K	A3K sw 464
A3W	A3W sw 464
A3WG6	A3WG6 sw LS 23189
B3WG6	B3WG6 sw 564
B3WG6	B3EG6 sw LS 23189
T KR4350	T KR4355G5 sw 564
T KR4355G5	T KR4355G5 sw 564
A3WG6 LT sw*	A3WG6 sw LS 23189
B3WG6 LT sw*	B3EG6 sw LS 23189

*Black transmitting component.

BASF: Ultramid

Suitable solvents for bonding Ultramid are those based on phenol or resorcinol.

Reference: *Ultramid Nylon Resins Product Line, Properties, Processing*, Supplier design guide (B 568/1e/4.91), BASF Corporation, 1991.

DuPont: Zytel

Occasionally, solvent welding is used to join parts of Zytel nylon resin to others of Zytel nylon resin or dissimilar materials such as wood, metal, or other plastics. This process is particularly applicable when joining large or complicated shapes. It is best suited to low-volume production or for prototype purposes because the long, labor-consuming bonding procedure is not easily or economically automated.

Regardless of the particular solvent used, the following general information applies to the assembly technique of solvent welding Zytel nylon:

- Lap joints or tongue and groove joints result in a much stronger bond than butt joints. Good contact is needed between the surfaces to be joined. In general, the larger the surface area, the stronger will be the joint.
- In parts to be flexed, the plane of the joint should be perpendicular to the line of the applied force. For example, a beam subjected to a vertical load should be assembled with an overlapped joint having the welded surfaces in a horizontal plane.
- A fabricating fixture is desirable as it prevents the dislocation of the surfaces after joining.

Three solvent types are particularly suggested for joining nylon to nylon. Aqueous phenol solvent, resorcinol-ethanol solvent, and nylon-bodied calcium chloride-ethanol solvent cement produce bonds that are nonembrittling, tough, and quick curing.

Aqueous Phenol: Aqueous phenol containing 10–15% water is the most generally used solvent mix for bonding Zytel nylon resin to itself. It can be purchased in this “liquified” form with 10–15% water from chemical supply houses, but must be used with caution. The bond achieved by use of this solvent is water resistant, flexible, and has high strength.

Directions for use:

(1) Thoroughly clean and dry both mating surfaces.

(2) If the parts fit together well, assemble them immediately. If the fit is poor or loose at the interface, wait two or three minutes after application of the aqueous phenol before assembling. This softens the surface and helps in obtaining a satisfactory fit. It is extremely important that the mating surfaces make contact while wet with aqueous phenol. If the mating surfaces become separated or dislocated after mating, more aqueous phenol should be applied, even if the surfaces are still tacky.

(3) Uniformly clamp the mating surfaces together under a pressure of approximately 10 psi (0.07 MPa). Higher pressures may be used, but the improvement is negligible.

(4) After clamping the surfaces together (spring clamps are acceptable), immerse the joint in boiling water. A curing time of about five minutes in boiling water should be sufficient to form a permanent weld in parts 3.2 mm (0.125 inches) in thickness. Slightly longer times should be used for thicker sections. This time will vary, of course, depending on the thickness of the piece. It is recommended that the joint be boiled until little or no odor of phenol is detected when the joint is removed from the water.

(5) Air curing at room temperature, while requiring a longer time to set, has been found to be a satisfactory method for many parts. This is particularly true if the two parts to be joined can be snapped together or made with a tight torque and groove joint, so that no clamping is required. Several days are required to get maximum joint strength, so a minimum of four days should be allowed before the joint is highly stressed. If faster curing is necessary, the parts can be cured in a circulating air oven at 66°C (150°F) for 30 minutes.

Warning: Both phenol and resorcinol must be handled with care. Phenol is volatile, presenting a breathing hazard. Under OSHA regulations 29 CFR 1910.1000 the 8-hour time weighted average exposure limit for phenol is 5 ppm in air. Resorcinol is less volatile than phenol but adequate ventilation must be provided to avoid inhalation of vapors. To prevent contact with skin, operators should wear goggles and impervious gloves, and should take care to prevent splashing on the skin or clothing. The action of resorcinol is very much the same and similar precautions should be taken. However, it is less volatile and acts more slowly on the skin. If either phenol or resorcinol comes in contact with the skin, it must be promptly and completely removed with copious amounts of water. In cases of gross contact, medical attention should be obtained. Neither phenol nor resorcinol should be used where the end-use involves contact with foods. For such applications, use nylon-bodied calcium chloride-ethanol.

Resorcinol-Ethanol: The most appealing attribute of a resorcinol-ethanol solution as a solvent is its convenience in use. Resorcinol is quite soluble in ethanol, and solutions for use as solvents can be made by combining equal parts by weight of resorcinol (technical or USP grade) and ethanol (95% or anhydrous commercial ethyl alcohol) and stirring or shaking at room temperature for 15–20 minutes. A 50–50 solution is convenient to prepare and gives some margin for the evaporation of ethanol in use. The concentration is not critical.

Directions for use:

(1) Thoroughly clean and dry both mating surfaces.
(2) Paint the solution generously on both surfaces with an ordinary, flat paint brush. The solution has a very low viscosity, and run-off from the painted surfaces is prevented by working the brush over the surfaces two or three times.
(3) After 20–30 seconds, the two mating surfaces soften enough so that they cannot be wiped dry by a close fit. The generous application of solvent and the waiting period are necessary to ensure strong, tight joints. Longer waiting periods (up to 3 minutes) will generally improve joint strength.
(4) After the softening period, press the mating surfaces together and clamp in place under light pressure for 10–15 minutes at which time the joint strength is adequate for light handling. The bond reaches a workable strength in about 90 minutes and approaches full strength in 24 hours. As with aqueous phenol, curing can be accelerated by heating in a circulating air oven at 66°C (150°F) for 30 minutes.

Nylon-Bodied Calcium Chloride-Ethanol: This solvent cement may be used in applications involving foods and potable water supplies. It is neither corrosive nor toxic, and has no disagreeable odor. There is no danger of skin burns. The recommended formulation for this solvent cement is 10 parts of Zytel 101 NC-10, 22.5 parts calcium chloride and 67.5 parts ethanol. Add 22.5 parts calcium chloride (analytical reagent grade) to 67.5 parts ethanol (95% or anhydrous commercial ethyl alcohol) and shake for 2 hours or until the calcium chloride is dissolved. Filter through a fritted glass funnel to clarify the cloudy solution. Add 10 parts of Zytel 101 NC-10, ground to pass a #10 screen and stir overnight. The resultant solution is a clear, honey-like solvent cement that will last indefinitely.

Directions for use:

(1) Paint the cement on the surfaces to be joined with a brush or cotton applicator.
(2) After about 30 seconds, assemble the parts and hold under contact pressure.
(3) After 30 minutes, the joint can be lightly handled, but 24 hours are required to attain the full bond strength.

Note: This solvent cement is not hazardous and no special precautions need to be taken to prevent skin burns. It is especially useful for nylon resin applications, where nontoxicity is desirable.

Reference: *Design Handbook for DuPont Engineering Plastics—Module II*, Supplier design guide (E-42267), DuPont Engineering Polymers.

25.1.8 Adhesive Bonding

Nylon

Nylon can be bonded using anaerobic, UV, epoxy and structural acrylic adhesives. The material should be dried at 60°C (140°F) for several hours prior to bonding. The surface should be abraded. It can be difficult to bond unfilled resins.

Reference: *The Engineers Guide to Adhesives*, Supplier design guide, Permabond Engineering Adhesives.

EMS-Chemie: Grilon, Grivory

The excellent resistance to chemicals of Grilon and Grivory makes them difficult materials to bond.

Cyanoacrylate or methacrylate single-component adhesives are particularly suited for bonding Grilon and Grivory to metal. Polyurethane and epoxy resin two-component adhesives can also be used for bonding Grilon and Grivory. A significant improvement in bond quality can be achieved through pretreatment to activate the bond areas. Pretreatments include:

- Degreasing: use of organic solvents, such as acetone
- Mechanical removal: brushing, grinding or sand blasting

- Electro-chemical: corona discharge or low-pressure plasma
- Thermal: flaming
- Chemical: treatment with caustic substances

References: *Grilon: The Traditional Product*, Supplier design guide, EMS-Chemie.

Grivory G Partially Aromatic Polyamides, Supplier design guide, EMS-Chemie.

Cadillac Plastic and Chemical Company: Cadco (manufacturing method: cast)

The nonstick and/or solvent-resistant nature of Cadco cast nylon requires that part surfaces be specially prepared before adhesive bonding can occur. The surfaces can then adhere to like substrates or others such as wood, steel, and aluminum.

Cadco cast nylon can be roughened with a medium grit emery cloth, but must also be cleaned before and after roughening. Methyl ethyl ketone solvent is recommended for cleaning.

Reference: *Cadco Engineering Plastics*, Supplier design guide (CP-200-92), Cadillac Plastic and Chemical Company, 1992.

BIP Chemicals: Beetle

Beetle and Jonylon nylon components can be bonded together, to other plastics, and to metals, using commercially available adhesives, such as epoxy, polyurethane, silicone, and cyanoacrylate.

Reference: *Beetle & Jonylon Engineering Thermoplastics,* Supplier marketing literature (BJ2/1291/SP/5), BIP Chemicals Limited, 1991.

DuPont: Zytel

A variety of thermosetting adhesives can be used to bond Zytel nylon resin to metals (Table 25.2).

Table 25.2. Examples of Adhesives Used for Bonding Zytel Nylon Resin to a Wide Variety of Substrates

Adhesive	Supplier
Resiweld 7004—Nylon to wood, metal and leather	H.B. Fuller Company; 1200 Willow Lake Boulevard; St. Paul, Minnesota 55164; USA
Resiweld 7006—Nylon to metal and vinyl stock	
Apco 5363	Applied Plastics Co., Inc.; 7320 South 6th Street; Oak Creek, WI 53154-2093; USA

Reference: *Design Handbook for DuPont Engineering Plastics—Module II*, Supplier design guide (E-42267), DuPont Engineering Polymers.

25.1.9 Mechanical Fastening

DuPont: Zytel, Minlon

Riveting: When riveting unmodified Zytel nylon, it is advisable to have the part conditioned to equilibrium moisture content before riveting, as in the dry state the material is too brittle. Impact modified materials such as Zytel ST and Zytel 408 nylon resins can be riveted in the dry-as-molded state.

Self-tapping Screws: Zytel nylon resin works well with thread-forming screws. Thread-cutting screws are still preferred unless repeated disassembly is necessary.

Thirteen percent glass-reinforced Zytel nylon resin materials and Minlon mineral-reinforced materials are best fastened with thread-cutting screws. In these more rigid materials, thread-cutting screws will provide high thread engagement, high clamp loads, and will not induce high residual stress that could cause product failure after insertion.

For 33% and 43% glass-reinforced Zytel nylon resins, the finer threads of the Type-T screw are recommended. Even with the fine pitch screws, backing out the screw will cause most of the threads in the plastic to shear, making reuse of the same size screw impossible. If fastener removal and replacement is required in this group of materials, it is recommended that metal inserts be used, or that the boss diameter be made sufficiently larger to accommodate the next larger diameter screw.

Tables 25.3 and 25.4 give the numerical values of the pull-out strengths, stripping torque and dimensions for Type-AB screws of various sizes.

Snap-fits: The suggested allowable strains for lug type snap-fits are given in Table 25.5.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I*, Supplier design guide, DuPont Company, 2002.

DuPont: Zytel

Applications of snap-fits include a thermal delay valve and an exhaust gas recirculation (EGR) delay valve in the automobile engine, used to reduce nitrous oxide emission. They have snap-fit housings that are able to withstand under-the-hood temperatures and

Table 25.3. Pull-out Load Performances for Various Screw Dimensions in Zytel and Minlon Polyamides

		Screw No.	6	7	8	10	12	14
		D_s, mm	3.6	4.0	4.3	4.9	5.6	6.5
		d_s, mm	2.6	2.9	3.1	3.4	4.1	4.7
		D_h, mm	8.9	10.0	10.8	12.2	14.0	16.2
		d_h, mm	2.9	3.3	3.5	4.1	4.7	5.5
Pull-out force	Zytel 101L NC010	N	2250	3250	3850	4300	5100	6400
	Zytel 79G13L	N	2200	3100	3400	3700	4400	5900
	Zytel 70G30HSL	N	2300	3200	3500	3900	4850	6200
	Minlon 10B140	N	3200	3330	5370	5690	8710	10220
	Minlon 11C140	N	2880	3200	3540	4510	5070	6480

D_s: Major diameter of screw thread; d_s: pitch diameter of screw; D_h: boss outside diameter; and d_h: boss hole diameter.

Table 25.4. Stripping Torque Performances for Various Screw Dimensions in Zytel and Minlon Polyamides

		Screw No.	6	7	8	10	12	14
		D_s, mm	3.6	4.0	4.3	4.9	5.6	6.5
		d_s, mm	2.6	2.9	3.1	3.4	4.1	4.7
		D_h, mm	8.9	10.0	10.8	12.2	14.0	16.2
		d_h, mm	2.9	3.3	3.5	4.1	4.7	5.5
Stripping torque	Zytel 101L NC010	Nm	1.6	2.5	3.6	5.0	7.0	10.0
	Zytel 79G13L	Nm	2.0	3.0	4.0	5.3	6.9	8.5
	Zytel 70G30HSL	Nm	2.5	3.5	4.8	6.3	8.0	10.0
	Minlon 10B140	Nm	2.4	3.5	4.8	6.4	10.2	13.8
	Minlon 11C140	Nm	2.5	3.0	4.3	6.0	7.3	11.3

D_s: Major diameter of screw thread; d_s: pitch diameter of screw; D_h: boss outside diameter; and d_h: boss hole diameter.

Table 25.5. Suggested Allowable Strains for Lug Type Snap-fits in Zytel Polyamides

Material	Allowable Strain, %	
	Used Once (new material)	Used Frequently
Zytel 101, dry	4	2
Zytel 101, 50% RH	6	3
Zytel GR, dry	0.8–1.2	0.5–0.7
Zytel GR, 50% RH	1.5–2.0	1.0

facilitate assembly. The molded parts merely snap together when pressure is applied.

Reference: *Dupont Glass-Reinforced Zytel Nylon Resin*, Supplier Technical Report (E-22693), DuPont, 1993.

BIP Chemicals: Beetle

The toughness of Beetle and Jonylon nylon permits the use of self-tapping screws, bolts, and rivets for joining moldings and the inclusion in the component design of snap-fit and press-fit connections.

Reference: *Beetle & Jonylon Engineering Thermoplastics*, Supplier Marketing Literature (BJ2/1291/SP/5), BIP Chemicals Limited, 1991.

BASF: Ultramid

Parts made from Ultramid can easily be joined using screws that form their own threads (self-tapping screws). Ultramid parts can be connected without difficulty to one another, or to parts made from other materials by means of rivets and bolts. Threaded metal inserts have proved to be effective for screw connections subjected to high stresses and which frequently have to be loosened and retightened. These are encapsulated during molding or attached subsequently in prepared holes by means of ultrasound or hot embedding. Snap-in and press-fit connections can also withstand high stresses. Ultramid's outstanding elasticity and strength, even at high temperatures, are particularly advantageous for this form of construction.

Reference: *The Processing of BASF Polyamides*, Supplier design guide, BASF Corporation.

25.2 Nylon 6

25.2.1 Heated Tool Welding

Bayer: Durethan

The recommended hot plate welding parameters for Durethan PA6 are:

- Hot plate temperature: 280–450°C (536–842°F)
- Joining pressure: 0.1–1.0 N/mm^2 (15–145 psi)

Durethan KU2-2140/30 has been developed specifically for hot plate welding. Its distinguishing features are a lower level of melting adhesion and a larger welding process window. This has been achieved by increasing the melt viscosity.

Reference: *Hot Plate Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

Bayer: Nylon 6 (reinforcement: glass fiber)

In principle, polyamide is weldable using the heated tool process. High weld strengths can be achieved with certain modified types and suitable machine parameters. Two nylon 6 materials investigated (Bayer KU 2 2140/30 modified and BKV 30) proved to be very suitable for series fabrication since almost constant results were obtained in spite of wide variations of the welding parameters. The strength only fluctuated within relatively small ranges. These good welding results with the polyamide material can only be attained in conjunction with the material modification (higher viscosity in the welding area) and with the innovative machine technology (very high acceleration rates and rapid travel movement of the slides). Depending on the material, it is still necessary to clean the heated tool more or less frequently.

Reference: Haberstroh E, Schulz J: Heated-tool butt welding of polyamide. *Welding and Cutting*, 1, p. 10, 2002.

Nylon 6 (reinforcement: glass fiber)

The welding parameters used were:

- Maximum temperature of hot plate: 380°C (716°F)
- Maximum pre-melt clamp force: 3.0 kN (670 lbf)
- Maximum pre-melt and melting time: 30 seconds
- Melt-down: 0.5–5.0 mm (0.02–0.2 inches)
- Maximum hold/sealing time: 15 seconds

Experiments were conducted using glass-fiber reinforcement in the range 0–45% (by weight).

Morphology studies using microscopy revealed the fiber-glass distribution and orientation in the bulk of the material and at the interface. Under optimized hot plate welding conditions, part of the glass fibers were found the orient perpendicular, or at least at an angle, to the weld plane, and they were also found to be crossing the interface. The maximum tensile strength of the weld was achieved in materials with 14–24% glass-fiber reinforcement (by weight).

Reference: Kagan VA: Joining of nylon based plastic components—vibration and hot plate welding technologies. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

Nylon 6 (reinforcement: 30% glass fiber)

In the case of the heated tool welding of glass fiber-filled polyamide, a material-specific limiting value with regard to the maximum attainable weld strength cannot be exceeded, even if the process parameters are optimized or even if the design of the heated tool surface and of the joining surface is modified. With the polyamides investigated, this limiting value corresponds to approximately 50% of the material-specific yield stress of the unwelded reference specimen. The flow processes necessary during joining caused transverse orientation of the glass fibers in the weld.

The optimum process conditions portrayed indicate that it is not possible to specify any standardization of process conditions to be complied with for the heated tool welding of polyamides. Parameter optimization by means of experimental investigations, must therefore be recommended for every material and for every application.

With current prerequisites, it is not possible to totally avoid melt residues on the heated tool. Therefore, the heated tool should be cleaned according to the degree of contamination. At very high heated tool temperatures which do not allow a coating to be used, a self-cleaning effect occurs in the case of unreinforced plastics as a result of the evaporation of the melt residues.

With regard to the processing conditions, a moisture content of less than 0.5 wt.%, which may be even lower depending on the material type, is recommended. Therefore, joining parts made of polyamide should be welded as soon as possible after their manufacture or, in the case of a lengthy storage duration, should be packed in an air-tight environment or should be dried.

Reference: Potente H, Brüßel A: Investigations into the heated-tool welding of polyamide. *Schweissen und Schneiden,* 51(4), p. 195, April 1999.

Nylon 6 (reinforcement: glass fiber)

The research results have shown that there is a material-specific limit on the maximum attainable weld strength for filled and reinforced material systems which cannot be exceeded, despite extensive variation of the process conditions.

The results of the parameter study conducted on glass-fiber reinforced polyamide 6 have shown that the attainable weld strength $\sigma_{schw(\varphi)}$ is a function of the following parameters:

- Glass fiber content, φ
- Yield stress of the unreinforced reference specimen, $\sigma_{GM(\varphi=0)}$
- Weld strength of the matrix material, $\sigma_{schw(\varphi=0)}$
- Yield stress of the glass fiber reinforced reference specimen, $\sigma_{GM(\varphi)}$

Reference: Potente H, Brüßel A: Welding behaviour of filled and reinforced thermoplastics with hot plate welding. ANTEC 1998, Conference proceedings, Society of Plastics Engineers, Atlanta, May 1998.

25.2.2 Ultrasonic Welding

Bayer: Durethan

At a frequency of 20 kHz, an amplitude of 30–50 μm is recommended for ultrasonic welding of Durethan polyamide 6.

Reference: *Ultrasonic Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

Nylon 6

This work describes the use of central composite design to examine the ultrasonic welding of nylon. Prior to welding, all samples were dried in a vacuum oven for 24 hours at 90°C (194°F).

Results showed that, in order to produce the strongest weld, within the limits of the designed experiment, the weld time and cooling time should be maximum (1 and 1.2 seconds, respectively), with the weld force at minimum (249 N; 56 lbf). When welding semicrystalline materials, high amplitudes are selected, and it is therefore important to use minimum weld force to prevent stresses being locked into the joint and prevent stalling of the machine during the horn start-up phase.

Reference: Froment ID, Taylor NS: Central composite design—an aid to weld optimisation. Joining Applications in Electronics and Medical Devices, ICAWT '98, Conference proceedings, Columbus, September/October 1998.

Nylon (features: 5.8 mm (0.23 inches) thick)

Nylon 6 can be ultrasonically bonded producing strong, neat stitches.

Reference: *Ultrasonic Sealing and Slitting of Synthetic Fabrics*, Supplier Technical Report, Sonic & Materials, Inc.

25.2.3 Vibration Welding

Nylon 6 (form: 3 mm (0.12 inch) thick plaques; filler: nanoclay)

This study evaluated the weldability of nylon 6 nanocomposites with 0, 5, and 8 wt.% total nanoclay loadings using vibration welding. A three-factor (weld pressure, weld amplitude and melt-down) and two-level design of experiments (DOE) was conducted to evaluate the weldability of these materials. The nylon nanocomposite plaques were dried in a vacuum oven at 25°C (77°F) for 72 hours before welding. The plaque dimensions were 150 × 100 × 3 mm (5.9 × 3.9 × 0.12 inches). The frequency of vibration was fixed near 210 Hz and the cooling pressure was the same as the welding pressure. The melt-down values were between 0.75 and 1.5 mm (0.03–0.06 inches) and the pressure was between 1 and 2 MPa (145–290 psi). The peak-to-peak amplitude was adjusted from 1.25 to 1.75 mm (0.05–0.07 inches).

It was found that the strength reduction for 5 and 8 wt.% nanocomposites, compared to the 0 wt.% weld strength, was 13% and 19%, respectively. These strength reductions were much lower than observed for polypropylene-based nanocomposites. This may be attributed to the in situ polymerization process that offers more uniform exfoliation.

Reference: Wu CY, DeWerth J: Vibration welding of nylon 6 nanocomposites. ANTEC 2006, Conference proceedings, Society of Plastics Engineers, Charlotte, May 2006.

DuPont: Zytel 73G30 HSL (form: 6 mm (0.24 inch) thick injection-molded plaques; reinforcement: 30% glass fibers)

Samples were welded dry as molded. All samples were butt welded with a weld area of 100 × 6 mm (3.9 × 0.24 inches). The vibration frequency was 210 Hz. Two levels of welding pressure (0.6 and 5 MPa; 87 and 725 psi) and two levels of welding amplitude (1.00 and 1.78 mm; 0.039 and 0.07 inches) were used, with 2 mm (0.079 inches) melt-down for all samples.

During vibration welding, fiber reorientation resulted from both squeeze flow in the x-direction and shear flow in the z-direction before the cooling phase. However, the final fiber reorientation was determined by the squeeze flow that occurred in the cooling phase, when the vibration had stopped. It appears that pressure during the cooling phase promotes fiber reorientation in both the squeeze flow direction and the tensile direction by relaxing the molecular orientation in the z-direction, which was caused by shear flow during vibration. Low amplitude must contribute less to the molecular and fiber orientation in the vibration direction compared to high amplitude. This should help high weld pressure reorient fibers toward the squeeze and tensile direction and thus enhance weld strength.

Thicker HAZ does not necessarily yield more random orientation overall but contains a higher number of fibers due to its thickness. High welding pressure plays an important role in fiber reorientation in the tensile direction when combined with low amplitude.

Reference: Chung YM, Gómez R, Kamal MR: Three dimensional fiber orientation in vibration welded joints of glass fiber reinforced polyamide-6. ANTEC 2005, Conference proceedings, Society of Plastics Engineers, Boston, May 2005.

DuPont: Nylon 6 (form: 3.1 mm (0.122 inch) thick injection-molded plaques)

Welding trials were carried out on unreinforced nylon 6 and nylon 66. Three geometries were studied: butt welds, T-welds with the lower melting nylon 6 on the web, and T-welds with nylon 6 on the flange. Welding was carried out at a nominal frequency of 211 Hz and a 1.78 mm (0.07 inch) peak-to-peak amplitude.

Over the range of conditions evaluated, unreinforced nylon 6/nylon 66 butt and T-weld strengths increased with decreasing weld pressure and increasing weld penetration. Under optimal conditions of low pressure and high melt-down, the butt weld strengths were approximately 70–80% of nylon tensile strengths.

Higher strengths were obtained for T-welds in which the lower melting nylon 6 was the web material. Maximum strengths could be improved by as much as 50% upon moving the lower melting material from the flange to the web.

Fracture surface analysis suggested that stronger welds were characterized by a high degree of mechanical interlocking between the two polymers. DSC analysis indicated that this interlocking was made possible by melting of both polymers at the interface.

Reference: Dyck C, Osti M, Bates PJ: Strength of vibration welds made from dissimilar nylons. ANTEC 2002, Conference proceedings, Society of Plastics Engineers, San Francisco, May 2002.

Honeywell International: Capron 8233G HS (form: injection-molded plaques; reinforcement: 33% short glass fibers)

Under optimized welding conditions, the tensile strength of straight butt joints was equal to or higher than the tensile strength of the base polymer (matrix). When optimized for weld geometry and glass-fiber reorientation, T-type butt joints can attain the same high mechanical performance as shown with straight butt joints.

Reference: Kagan VA, Roth C: The effects of weld geometry and glass-fiber orientation on the mechanical performance of joints—Part 1: weld design issues. ANTEC 2002, Conference proceedings, Society of Plastics Engineers, San Francisco, May 2002.

DuPont: Zytel 73G30 (reinforcement: 30% glass fibers)

Two weld geometries were studied: T-welds and cylindrical shape, referred to as a weld-cap-fixture (WCF), welded to a flat plaque. The materials used for the T-welds were nylon 6, nylon 66, and polyphthalamide (PPA), all glass-fiber reinforced. The materials used for the WCF welds were nylon 6 and nylon 66 (all glass-fiber reinforced).

The T-weld welding parameters were:

- Frequency: 230 Hz (approximate)
- Weld pressure: 2.2 MPa (319 psi)
- Amplitude: 1.8 mm (0.070 inches)
- Weld time: 3 seconds
- Hold time: 3 seconds

The WCF welding parameters were:

- Frequency: 232.6 Hz
- Weld pressure: 1.4 and 4.1 MPa (203 and 595 psi)
- Amplitude: 1.8 mm (0.070 inches)
- Weld time: 2–9 seconds
- Hold pressure: 1.4 and 4.1 MPa (203 and 595 psi)
- Hold time: 8 seconds
- Weld depth: 1.14 mm (0.045 inches)

All the trials demonstrated that, when there is a melt temperature difference between the materials, the weld depth is primarily achieved by the melting and consequent erosion of the material with the lower melt temperature. Although the actual values were different, there were similar trends in both the T-weld data and the WCF weld data. For example, the best welds were generally obtained when the melt temperatures were the same, or similar and the worst welds were obtained when the melt temperature difference was greatest.

For the heterogeneous welds on materials containing long glass fibers, whereas the melt temperature differences between the materials being welded ranged from 15–72°C (27–130°F), the weld strengths barely varied.

This data showed that it should be possible to get good welds between PA6 (and PA66) and PPA.

Reference: LeBlanc V, Baylis B, Qi L, Watt D: Vibration welding of dissimilar nylons. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

Allied Signal: Capron 8233 (form: injection molded plaques; reinforcement: 25% short glass fibers)

This work compares the differences in weld quality between orbital and linear vibration welding of various thermoplastics. The control parameters were varied as follows:

- Amplitude: 0.76–1.8 mm (0.03–0.07 inches) peak-to-peak
- Clamping pressure: 1.0–6.9 MPa (145–1000 psi)
- Collapse: 0.76–1.8 mm (0.03–0.07 inches)

Results showed that there was little difference in the maximum weld strength between linear and orbital welding. Therefore, orbital welding enables a 30% or more reduction in cycle time without loss in maximum weld strength.

For a given clamping force setting, with orbital motion it was possible to weld with a 5% lower vibration amplitude and achieve the same weld strength as with a linear motion. The advantage of lower minimum vibration amplitude for welding is the ability to weld higher unsupported walls and the ability to design more massive tooling for larger parts without overloading the welding machine.

Reference: Grewell DA, Benatar A: An application comparison of orbital and linear vibration welding of thermoplastics. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

Nylon 6 (reinforcement: glass fiber)

The linear vibration welding parameters used were:

- Weld amplitude: 1.02–1.80 mm (0.04–0.07 inches)
- Melt-down: 0.5–5.0 mm (0.02–0.2 inches)
- Weld frequency: 210 Hz
- Hold/cooling time: 2–10 seconds
- Maximum clamp force: 3.6 kN (810 lbf)
- Driven platen fixture weight: 2 kg (4.4 lb)

The orbital vibration welding parameters used were:

- Weld amplitude: 0.25–1.50 mm (0.01–0.06 inches)
- Melt-down: 0.5–2.0 mm (0.02–0.08 inches)
- Weld frequency: 190 Hz
- Hold/cooling time: 2–10 seconds
- Maximum clamp force: 0.5 kN (110 lbf)
- Driven platen fixture weight: 2 kg (4.4 lb)

Experiments were conducted using glass-fiber reinforcement in the range 0%–50% (by weight).

Morphology studies using microscopy revealed the fiber-glass distribution and orientation in the bulk of the material and at the interface. Under optimized vibration welding conditions, part of the glass fibers were found to orient perpendicular, or at least at an angle, to the weld plane, and they were also found to be crossing the interface.

Comparing studies of linear vibration and orbital vibration joining technologies demonstrated that the orbital vibration welding process is very efficient for nylons, and may be used as an alternative to linear vibration welding and ultrasonic technologies for welding small components.

For linear vibration welding, the maximum tensile strength of the weld was achieved in materials with 14–24% glass-fiber reinforcement (by weight).

Reference: Kagan VA: Joining of nylon based plastic components—vibration and hot plate welding technologies. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

Allied Signal: Capron (reinforcement: glass fiber)

For nylon 6 with 0–50% glass fiber reinforcement, the tensile strength of vibration welded butt joints under optimized welding conditions (maximum clamp load: 4.5 kN (1000 lbf); weld amplitude: 1.02–1.80 mm (0.04–0.07 inches); weld time: 4–25 seconds; weld frequency: 240 Hz) was found to peak between 14% and 25% glass-fiber content. This weld strength (90.2–90.7 MPa; 13,082–13,155 psi) is 10–17% higher than the nonreinforced material. Analysis of the welding interface by optical and scanning electron microscopy suggested that the thickness of the weld zone also displays a maximum (>300 μm; 0.012 inches) at 14–25% glass-fiber content.

Results of the microscopy study showed that in samples that achieve maximum tensile strength under optimized welding conditions, some of the fibers reorient along the tensile direction (perpendicular to the weld plane) and may even cross the interface. It is postulated that the high tensile strength measured from these weld joints is a result of increased thickness of the weld zone, which may provide mobility to the fiber to reorient towards the tensile direction.

Reference: Kagan V, Lui S, Smith GR: The optimized performance of linear vibration welded nylon 6 and nylon 66 butt joints. ANTEC 1996, Conference proceedings, Society of Plastics Engineers, Indianapolis, May 1996.

25.2.4 Laser Welding

Nylon 6 (form: 3 mm (0.118 inch) thick injection molded plaques; features: heat stabilized)

Laser-transmissible (natural) and laser-absorbing (colored by carbon black) grades of unfilled and 33 wt.% fiber-glass reinforced nylon 6 was used in this study. They were sealed prior to welding, testing, or conditioning to maintain a targeted level of absorbed moisture. The processing parameters were:

- Wavelength: 940 ± 10 nm
- Power range: 20–50 W
- Laser beam quality: spot (1.5–2.0 mm; 0.059–0.079 inches)
- Speed: 5–15 mm/s (0.2–0.6 inches/s)
- Clamping pressure: 0.5–1.5 MPa (73–218 psi).

Results indicated that moisture (up to 7%) is not a barrier for through transmission laser welding (TTLW) and mechanical performance of the welded parts. Under the conditions of optimized welding processing, the tensile strength of laser welded dry-as molded nylon 6 was equal/close to the tensile strength of frictional (linear vibration and orbital vibration) or hot plate welded joints. The shear strength of a diode-laser welded lap joint depends on the amount of moisture that the nylon has been exposed to and does not depend on the content of fiber-glass reinforcement. In this study, no evidence was observed relating the significance of moisture (up to 4 wt.%) to laser-energy transmission in nylon. The TTLW technology is more efficient in welding of ‘wet’ nylon than ultrasonic welding, and gives similar mechanical performance to linear-vibration welded material.

Reference: Kocheny SA, Kagan VA, Macur J: Through-transmission laser welding of nylon—breaking the moisture barrier. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

DuPont: Zytel 7301 (features: unreinforced)

This study examined the effect of diode laser speed, power, beam area, and weld pressure on the melt-down, microstructure and weld strength of T-joints made from unreinforced nylon 6. The laser-absorbing part (web) was made from natural, unreinforced nylon 6 compounded with 0.21 wt.% carbon black. The laser used in this study was a 150 W continuous-wave diode laser with a focal distance of 100 mm (3.94 inches). The theoretical laser beam area depends on the distance between the weld interface and the laser optic. This distance is referred to as the working distance of the laser. The beam area increases with increasing working distance beyond the focal plane of the beam. The laser power and speed ranged from 60 to 100 W and 450–1500 mm/minute (17.7–59.0 inches/minute), respectively. The weld pressure was varied between 0.7 and 4.5 MPa (102–653 psi).

Melt-down of unreinforced nylon 6 increases with increasing line energy, working distance, and weld pressure. The minimum line energy required to generate melt-down was estimated to be between 2 and 3 J/mm. Weld strength also increased with increasing working distance. At high working distances, a uniform HAZ thickness was obtained, which resulted in the formation of strong welds.

Reference: Prabhakaran R, Kontopoulou M, Zak G, Bates PJ, Baylis B: Laser transmission welding of unreinforced nylon 6. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

Nylon 6 (form: injection-molded plaques)

The welding trials were carried out using a diode laser operating at a wavelength of 940 nm ± 10 nm, an output power range between 15 and 150 W and a beam size between 2.5 and 4.5 mm (0.10–0.18 inches). The optimized clamping pressure was in the range 1.0–1.2 MPa (145–174 psi).

The tensile strengths of the clear-weld butt joints were greater than 82% of parent strength for unreinforced nylon 6, 84.3% of parent strength for 14 wt.% glass-filled nylon 6, and 83.7% of parent strength for 33 wt.% glass-filled nylon 6.

Reference: Kagan VA, Woosman NM: Efficiency of clear-welding technology for polyamides. ANTEC 2002, Conference proceedings, Society of Plastics Engineers, San Francisco, May 2002.

Allied Signal: Capron

The laser transmittance of the following color versions were evaluated at two wavelengths (830 nm and 1064 nm): natural, red (organic), yellow (organic), green (organic), white (inorganic), black (carbon black, 0.2–2.0 wt.%), black (noncarbon black, laser admissable, 0.25–1.0 wt.%).

All versions of carbon-black pigmented plastics did not transmit laser energy at near infrared wavelengths. Very low transmittance was found for green and white color versions (less than 10%). The red-colored PA6 had a high transmittance, very close to the natural state. The specimens colored yellow had significantly reduced transmittance relative to natural and red. This reduction is wavelength-independent in the near infrared, and most likely to be due to diffuse light scattering. The reduced transmittance at 830 nm relative to 1064 nm for the green specimens most likely represents the intrinsic absorption of the colorant.

Reference: Kagan VA, Chambers A, Bray RG: Forward to better understanding of optical characterization and development of colored polyamides for the infra-red/laser welding: Part II—family of colored polyamides. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

Allied Signal: Capron (material composition: glass-fiber reinforcement, mineral fillers, impact modifiers, colorants)

Welds were made using a Nd:YAG laser (wavelength 1.06 μm).

For the 3.2 mm (0.125 inch) thick short fiber-glass reinforced nylon 6 plastics, the laser energy transmission decreased monotonically (from 70 to 20%) with increasing fiber-glass content from 0 to 63%. Mineral fillers were more effective in energy reduction (transmission was 6.5% for 40 wt.%, which was five times less than for 45 wt.% fiber-glass). Impact modifiers reduced laser transmission by 50%.

Plastics of different colors displayed marked differences in transmission of the laser energy. Transmission of red specimens was close to natural color, while yellow and green colors reduced the transmission by 75%–85%. Carbon black reduced transmission to extremely low levels.

For noncolored nylon 6, the laser energy transmission decreased monotonically (from 85 to 42%) with increasing thickness of the molded plaque/part, from 0.8 to 6.25 mm (0.031 to 0.246 inches).

Reference: Kagan VA, Bray RG, Kuhn WP: Laser transmission welding of semi-crystalline thermoplastics—Part I: optical characterization of nylon-based plastics. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

Allied Signal: Capron 8202 (reinforcement: glass fiber)

In this study a diode laser with the following parameters was used:

- Wavelength: 808 nm ± 10 nm
- Power range: 20–100 W
- Laser beam quality: minimum focus size—0.8 mm (0.031 inches) diameter
- Working distance: 32–150 mm (1.26–5.91 inches)

Transmission laser welding was performed on injection molded T-type specimens having a butt joint.

At optimized processing conditions, the mechanical performance (tensile strength at 23°C; 73°F) of laser welded nylon 6 is equal/close to the tensile strength of vibration or hot plate welded joints.

Reference: Kagan V, Pinho GP: Laser transmission welding of semi-crystalline thermoplastics—Part II: analysis of mechanical performance of welded nylon. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

25.2.5 Induction Welding

Nylon 6 (form: injection-molded bowls; reinforcement: 33% glass fiber)

For the present study a tongue-in-groove joint, using a 3.4 mm (0.134 inch) thick and 6.65 mm (0.262 inch) long tongue was molded into the upper shell and a mating groove was molded into the lower shell. The welded test samples were connected to a portable hydrostatic tester at room temperature; burst testing was conducted within 1 hour of induction welding.

The optimized conditions were identified as 11 seconds weld time at low pressure, 5 seconds weld time at high pressure, and 20 seconds cooling time. The low pressure force applied during welding was 186.5 kgf per meter (10.5 lbf per inch) of bondline. The high pressure force applied was 840.5 kgf/m (47.1 lbf/inch) of bondline. The average burst strength was 1.33 MPa (192 psi).

The common failure mode observed (fracture through the tongue) suggests that further strength optimization can be obtained by redesign of the joint to increase the thickness of the tongue. The apparent strength limitation in this element appears to be dependent upon the distribution of the reinforcing glass fibers in the local region.

References: Nichols RJ, Kagan VA: Induction welding takes new aim for reinforced thermoplastics in high strength and load bearing applications. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

25.2.6 Adhesive Bonding

Allied Signal: Capron 8202

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 25.6 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually as shown in Table 25.6, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in “real world” applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 and Super Bonder 414 instant adhesives achieved the highest bond strengths, typically in excess of 4000 psi (27.6 MPa).

Table 25.6. Shear Strengths of Capron 8202 Nylon 6 to Nylon 6 Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[b]

Material Composition		**Loctite Adhesive**					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	11 rms	2450 (16.9)	4500 (31.0)	1600 (11.0)	4100 (28.3)	450 (3.1)	1400 (9.7)
Roughened	15 rms	2450 (16.9)	4500 (31.0)	1600 (11.0)	4100 (28.3)	450 (3.1)	1400 (9.7)
Antioxidant	0.35% Irganox B1171	2450 (16.9)	4500 (31.0)	250 (1.7)	4100 (28.3)	450 (3.1)	1400 (9.7)
UV stabilizer	0.63% Chimasorb 944	2450 (16.9)	4500 (31.0)	1600 (11.0)	4100 (28.3)	450 (3.1)	1400 (9.7)
Impact modifier	5% EXL 3607	>2200[a] (>15.2)[a]	>4500[a] (>31.0)[a]	>1650[a] (>11.4)[a]	>4300[a] (>29.7)[a]	450 (3.1)	1400 (9.7)
Flame retardant	18% PO-64P 4% Antimony Oxide	1700 (11.7)	4500 (31.0)	1600 (11.0)	4100 (28.3)	450 (3.1)	1400 (9.7)
Lubricant #1	0.5% Aluminum Stearate	1450 (10.0)	4500 (31.0)	350 (2.4)	4600 (31.7)	450 (3.1)	1400 (9.7)
Lubricant #2	0.5% Mold Wiz INT-33PA	2450 (16.9)	>4500[a] (>31.0)[a]	550 (3.8)	>3750[a] (>25.9)[a]	450 (3.1)	1050 (7.2)
Glass filler	30% Type 3450 Glass Fiber	2450 (16.9)	>4700[a] (>32.4)[a]	150 (1.0)	>4450[a] (>30.7)[a]	450 (3.1)	1400 (9.7)
Talc filler	30% Mistron CB Talc	2450 (16.9)	2200 (15.2)	2100 (14.5)	2750 (19.0)	450 (3.1)	1400 (9.7)
Plasticizer	4% Ketjen-Flex 8450	3300 (22.8)	>4550[a] (>31.4)[a]	650 (4.5)	>4450[a] (>30.7)[a]	450 (3.1)	1400 (9.7)
Antistatic	5% Larostat HTS 906	2450 (16.9)	>3100[a] (>21.4)[a]	350 (2.4)	>4100[a] (>28.3)[a]	450 (3.1)	1400 (9.7)

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

Black Max 380 instant adhesive achieved the second highest bond strengths, followed by Loctite 3105, a light curing acrylic adhesive. Flashcure 4305 light cure adhesive also achieved a bond strength that resulted in substrate failure. Fixmaster rapid rubber repair and Hysol 3651 hot melt adhesive achieved the lowest overall bond strength. All other adhesives tested generally achieved good bond strength.

Surface Treatments: Surface roughening caused a statistically significant increase in the bond strengths achieved when using Depend 330, but it did not have any statistically significant effect with any of the other adhesives. The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused either no effect, or a statistically significant decrease in the bondability of nylon 6, on all of the formulations that were evaluated.

Other Information: Polyamide is compatible with all Loctite adhesives, sealants, primers, and activators.

Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

25.2.7 Mechanical Fastening

Bayer: Durethan BKV 30H (reinforcement: 30 wt.% short glass fiber)

In this work, the static and dynamic load limits of mechanical fasteners (insert/self-tapping screw) were determined. Glass-fiber reinforced polyamide 6 was used for injection molded boss test specimens. The boss geometry was kept constant (wall thickness: 4.5 mm (0.177 inches), boss length: 26 mm (1.024 inches), pilot hole diameter: 4.0 mm (0.157 inches)), except for the pilot hole diameter for the threaded inserts, which was reamed to between 5.8 (0.228 inches) and 8.5 mm (0.335 inches), according to the insert. All boss specimens for self-tapping screws had a lead-in section with a diameter of the normal screw (5.0 mm; 0.197 inches) to a depth of 2.0 mm (0.079 inches). The moisture content of the polyamide specimen was about 1.5 ± 0.2 wt.%.

Beside self-tapping screws, standard commercial hot-embedded threaded brass inserts and ultrasonic-embedded plastic inserts, in sizes M4 and M5, were examined. The plastic inserts were made of semiaromatic copolymer based on PA6-GF60.

In the dynamic tensile test, the applied waveform was sinusiodal at a constant minimum-to-maximum load ratio of 0.1. The test frequency was 5 Hz, and tests were performed at 23°C (73°F) and at 50% relative humidity.

The static pull-out limit of joints with brass inserts (size M5) was comparable to joints with plastic inserts (size M5) as well as self-tapping screws (5 mm; 0.197 inches diameter). The joints failed via pull-out of the insert or self-tapping screw. The dynamic load limit, as measured in a stepwise dynamic load increase test for self-tapping screws and plastic inserts was about 3.4 kN (760 lbf), and about 3.0 kN (670 lbf) for the brass inserts. The joints failed via boss fracture (brass insert), thread pull-out/shear-off (plastic insert), and screw pull-out (stepwise load increase test), or screw fracture (single-load test).

Reference: Tome A, Ehrenstein GW, Dratschmidt F: Joint performance of mechanical fasteners under dynamic load. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

Bayer: Durethan BKV 30H (reinforcement: 30 wt.% short glass fiber)

Glass-fiber reinforced polyamide 6 was used for injection-molded boss test specimens. The boss geometry was kept constant (wall thickness: 4.5 mm; 0.177 inches, boss length: 26 mm; 1.024 inches) except for the pilot hole diameter, which was varied between 3.8 and 4.0 mm (0.150–0.157 inches). The humidity of the polyamide specimens was about 1.5 wt.%. Both screws had a single lead thread without a cutting slot, a wide thread spacing (P ~ 0.44d), small core diameters (d_{core} ~ 0.54d) and small thread angles (a = 30°).

At ambient temperatures, decreases in the initial prestress force of about 30% were measured; at 80°C (176°F) decreases of about 60% were measured. While the decrease at an ambient temperature is slowed after a few hours and reaches an asymptotic value, the relaxation speed at 80°C (176°F) is not as significantly slowed, even after approximately 1000 hours. This depends probably on the exceeded glass transition temperature of PA6-GF30, which is about 25°C (77°F).

To reduce the surface pressure between the flank of the screw and the thermoplastic boss, it is possible to enlarge the engagement length or to reduce the pilot-hole diameter. The enlargement of the screw engagement length leads to a higher prestress load level with a similar relaxation rate. The reduction of the pilot hole diameter also leads to a higher prestress force level. In contrary to larger screw engagement lengths, the relaxation rate for a smaller pilot hole at 80°C (176°F) is also smaller.

Reference: Tome A, Ehrenstein GW: Time dependent prestress force of threaded joints in glass fiber reinforced polyamide at elevated temperatures. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

Bayer: Durethan BKV 30H (reinforcement: 30 wt.% short glass fiber)

The sensitivity and precision of the hysteresis measurement method makes it suitable for determining the dynamic load limits of threaded joints in PA6-GF30. Stepwise load increase experiments allow these limits to be determined in a few (1–2) hours. Measurements of the hysteresis between the load and time-dependent stiffness can be used to determine the mechanical properties of the joints.

In contrast to the load level, a decrease in the stiffness and a nonlinear increase in the system damping characterizes irreversible damage and the initiation of joint failure before screw pull-out. Increases in damping depend on the joint, for example, on the stiffness and the load-displacment behavior of the tightened part and the preload force. In non-preloaded joints, the damping begins to increase before the stiffness begins to decrease. Just the opposite is true of preloaded joints. The loss of the preload force is characterized by a significant increase in damping. In joints in which the damping increases and the stiffness decreases, optical micrographs show crack formation in the boss initiating at the top of the screw thread flank. Tests on self-threaded joints with specially designed screws show that they are capable of supporting high dynamic loads. With preload, these joints can attain lives in the range of 10^6 cycles. The dynamic load for normal screw engagement lengths is limited by the strength of the screw.

Reference: Dratschmidt F, Ehrenstein GW: Threaded joints in glass fiber reinforced polyamide. P*olymer Engineering and Science,* 37(4), p. 744, April 1997.

25.3 Nylon 66

25.3.1 Heated Tool Welding

DuPont: Zytel

One of the main problems in welding Zytel nylon 66 is oxidization and speed of crystallization. The surface of the joint is exposed to cold air when the hot plate is removed to allow the two parts to come together. During this time, the plastic will tend to oxidize and result in a poor weld. But with care and attention to certain parameters, Zytel can be hot plate welded to give a weld of good strength in relation to the parent material strength.

The Zytel must be dry as molded. Welding immediately after molding is the ideal case, although a delay of 48 hours is acceptable. If this is not practical, the parts must be dried to moisture content below 0.2%. The effect of moisture on the weld quality is quite dramatic. A frothy weld flash will be observed indicating a "wet" material; moisture will promote oxidization and porosity in the weld and thus reduces the strength of the weld by up to 50%.

Fillers in the plastic will also affect the weld strength. The strongest joint will be achieved with the natural unreinforced nylon. Glass fibers will obviously not weld to each other and will not move across the weld joint, which gives a similar weakness as a weld line in a molded part, up to 50% reduction in strength. The strength of the joint is inversely proportional to the glass content. Carbon black will also adversely affect the weld quality.

Normally, as a general rule, the temperature of the plate is set to +20°C (36°F) above the melt temperature of the plastic to be welded. In the case of Zytel nylon 66 with a melt temperature of 262°C (504°F), the plate temperature would be around 285°C (545°F). Attention must now be paid to the Teflon PTFE coating on the plates to avoid sticking, because at this temperature, the Teflon coating will start to fume off. To avoid this problem, the temperature of the plate should be 265–270°C (509–518°F). This is below the +20°C (36°F) rule, so a longer heat soak time should be used to compensate for the lower temperature. Another problem with welding at elevated temperatures is that at around 275°C (527°F), the aluminum plate will warp. To overcome this problem, aluminum bronze plates should be used; these can go up to 500°C (932°F).

Reference: *DuPont Engineering Polymers. General Design Principles—Module I*, Supplier design guide, DuPont Company, 2002.

Nylon 66 (reinforcement: glass fiber)

The welding parameters used were:

- Maximum temperature of hot plate: 380°C (716°F)
- Maximum pre-melt clamp force: 3.0 kN (670 lbf)
- Maximum pre-melt and melting time: 30 seconds
- Melt-down: 0.5–5.0 mm (0.02–0.2 inches)
- Maximum hold/sealing time: 15 seconds

Experiments were conducted using glass-fiber reinforcement of 0% and 33% (by weight).

Morphology studies using microscopy revealed the fiber-glass distribution and orientation in the bulk of the material and at the interface. Under optimized hot plate welding conditions, some of the glass fibers were found the orient perpendicular, or at least at an angle, to the weld plane, and they were also found to be crossing the interface.

Reference: Kagan VA: Joining of nylon based plastic components—vibration and hot plate welding technologies. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

25.3.2 Ultrasonic Welding

DuPont: Zytel 101, Zytel 408, Minlon

Parts molded of Zytel 101 and other basic 66 nylons can be welded with ease. An additional requirement, however, is that parts must be in a "dry-as-molded" condition. Parts molded of Zytel 408 and other modified

66 nylons may be ultrasonically welded, but with slightly greater difficulty than Zytel 101. The slightly lower stiffness of these resins may cause some problems with marring and formation of flash under the welding horn.

Minlon contains 40% mineral filler which allows an outstanding welding speed. However, we have noticed a certain sensitivity of molded parts to sharp angles, badly cut gates, or any other weak areas which can break under ultrasound; particular attention must be paid to the design of the part, more especially for Minlon 10B140.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I,* Supplier design guide, DuPont Company, 2002.

DuPont: Zytel GRZ (reinforcement: glass fiber)

Because of the glass fibers, glass-reinforced Zytel (GRZ) may need more weld area than unreinforced Zytel. When joining any nylon with this method, the plastic should also be dry as molded since moisture degrades weld strength.

Reference: *Dupont Glass-Reinforced Zytel Nylon Resin*, Supplier technical report (E-22693), DuPont, 1993.

Nylon (features: 5.8 mm (0.228 inches) thick)

Nylon 66 can be ultrasonically bonded producing strong, neat stitches.

Reference: *Ultrasonic Sealing and Slitting of Synthetic Fabrics*, Supplier Technical Report, Sonic & Materials, Inc.

25.3.3 Vibration Welding

DuPont: Nylon 66 (form: 3.1 mm (0.122 inch) thick injection-molded plaque)

Welding trials were carried out on unreinforced nylon 6 and nylon 66. Three geometries were studied: butt welds, T-welds with the lower melting nylon 6 on the web, and T-welds with nylon 6 on the flange. Welding was carried out at a nominal frequency of 211 Hz and a 1.78 mm (0.07 inch) peak-to-peak amplitude.

Over the range of conditions evaluated, unreinforced nylon 6/nylon 66 butt and T-weld strengths increased with decreasing weld pressure and increasing weld penetration. Under optimal conditions of low pressure and high melt-down, the butt weld strengths were approximately 70–80% of nylon tensile strengths.

Higher strengths were obtained for T-welds, in which the lower melting nylon 6 was the web material. Maximum strengths could be improved by as much as 50% upon moving the lower melting material from the flange to the web.

Fracture surface analysis suggested that stronger welds were characterized by a high degree of mechanical interlocking between the two polymers. DSC analysis indicated that this interlocking was made possible by melting of both polymers at the interface.

Reference: Dyck C, Osti M, Bates PJ: Strength of vibration welds made from dissimilar nylons. ANTEC 2002, Conference proceedings, Society of Plastics Engineers, San Francisco, May 2002.

DuPont: Nylon 66

Two general-purpose Nylon 66 compounds, one reinforced with 33% glass fiber and the other unreinforced, were used. Materials were welded dry as molded.

Three weld geometries were prepared: butt welds (weld area 133 × 3.2 mm; 5.24 × 0.126 inches); T-welds; and cups of nominal diameter 68 mm (2.677 inches). The clamp pressure was varied from 0.38 to 4.62 MPa (55–670 psi), the vibration frequency was set at 210 Hz, and the peak-to-peak amplitude (2a) was fixed at 1.78 mm (0.07 inches). The meltdown distance was recorded.

Results showed that glass-fiber filled nylon compounds melt down slightly faster than unfilled materials. Butt welds melt down much faster than T-welds, which both melt down significantly faster than cup welds. These differences are attributed to actual weld width and the vibration motion perpendicular to the weld bead direction.

Reference: Bates PJ, MacDonald J, Sidiropoulos V, Liang H: Meltdown-time profiles of vibration welded nylon 66 compounds. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

DuPont: Nylon 66 (reinforcement: glass fiber)

Nylon 66, reinforced with 33% glass fibers were welded and tested dry as molded. All samples were butt welded, with a weld area of 133 × 3.2 mm (5.24 × 0.126 inches).

The vibration frequency was 210 Hz; the peak-to-peak amplitude was fixed at 1.78 mm (0.07 inches) and the holding time was 30 seconds for all welds. The clamp pressure was varied between 0.5 and 4.0 MPa

(73–580 psi), and the melt-down values were varied between 1 and 2 mm (0.039–0.079 inches).

The SEM of the fracture surfaces suggested that glass fibers accumulate at the weld interface. The fibers were also seen to be preferentially oriented in the vibration direction in the plane of the fracture surface. The degree of orientation depended on the clamping pressure: lower pressures caused more orientation in the direction of flash flow.

Thermal gravimetric analysis confirmed that the glass-fiber content was higher at the weld interface than in the bulk. It is hypothesized that fibers are partially restrained from flow, as some of their length is immobilized by unmelted polymer. Unrestrained melt leaves the interface as flash. The fibers then accumulate at the interface.

Reference: Bates PJ, Mah JC, Liang H: Microstructure of vibration welded nylon 66 joints. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

DuPont: Zytel 70G33 (reinforcement: 33% glass fibers)

Two weld geometries were studied: T-welds and cylindrical shape, referred to as a weld-cap-fixture (WCF), welded to a flat plaque. The materials used for the T-welds were nylon 6, nylon 66, and polyphthalamide (all glass-fiber reinforced). The materials used for the WCF welds were nylon 6 and nylon 66 (all glass-fiber reinforced).

The T-weld welding parameters were:

- Frequency: 230 Hz (approximate)
- Weld pressure: 2.2 MPa (319 psi)
- Amplitude: 1.8 mm (0.07 inches)
- Weld time: 3 seconds
- Hold time: 3 seconds

The WCF welding parameters were:

- Frequency: 232.6 Hz
- Weld pressure: 1.4 and 4.1 MPa (203 and 595 psi)
- Amplitude: 1.8 mm (0.07 inches)
- Weld time: 2–9 seconds
- Hold pressure: 1.4 and 4.1 MPa (203 and 595 psi)
- Hold time: 8 seconds
- Weld depth: 1.14 mm (0.045 inches)

All the trials demonstrated that when there is a melt temperature difference between the materials, the weld depth is primarily achieved by the melting and consequent erosion of the material with the lower melt temperature. Although the actual values were different, there were similar trends in both the T-weld data and the WCF-weld data. For example, the best welds were generally obtained when the melt temperatures were the same or similar and the worst welds were obtained when the melt temperature difference was greatest.

For the heterogeneous welds on materials containing long glass fibers, whereas the melt temperature differences between the materials being welded ranged from 15–72°C (27–130°F), the weld strengths barely varied.

This data showed that it should be possible to get good welds between PA6 (and PA66) and PPA.

Reference: LeBlanc V, Baylis B, Qi L, Watt D: Vibration welding of dissimilar nylons. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

Nylon 66 (reinforcement: glass fiber)

The linear vibration welding parameters used were:

- Weld amplitude: 1.02–1.80 mm (0.04–0.07 inches)
- Melt-down: 0.5–5.0 mm (0.02–0.20 inches)
- Weld frequency: 210 Hz
- Hold/cooling time: 2–10 seconds
- Maximum clamp force: 3.6 kN (810 lbf)
- Driven platen fixture weight: 2 kg (4.4 lb)

The orbital vibration welding parameters used were:

- Weld amplitude: 0.25–1.50 mm (0.01–0.06 inches)
- Melt-down: 0.5–2.0 mm (0.02–0.08 inches)
- Weld frequency: 190 Hz
- Hold/cooling time: 2–10 seconds
- Maximum clamp force: 0.5 kN (110 lbf)
- Driven platen fixture weight: 2 kg (4.4 lb)

Experiments were conducted using glass-fiber reinforcement of 0% and 33% (by weight).

Morphology studies using microscopy revealed the fiber-glass distribution and orientation in the bulk of the material and at the interface. Under optimized vibration welding conditions, part of the glass fibers were found to orient perpendicular, or at least at an angle to the weld plane, and they were also found to be crossing the interface.

Comparing studies of linear vibration and orbital vibration joining technologies demonstrated that the orbital-vibration welding process is very efficient for nylons, and may be used as an alternative to linear-vibration welding and ultrasonic technologies for welding small components.

Reference: Kagan VA: Joining of nylon based plastic components—vibration and hot plate welding technologies. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

ICI: Maranyl A125

Plaques were dried for 12 hours in a vacuum oven at 95°C (203°F) before welding. The following welding conditions were used:

- Frequency: 200 Hz
- Weld pressure: 2.0 N/mm^2 (290 psi)
- Amplitude: 1.7 mm (0.067 inches)
- Welding time: 2–7 seconds
- Displacement: 0.18–1.88 mm (0.007–0.074 inches)
- Cooling time: 3 seconds

Results showed that the weld crystallinity was similar to, or slightly greater than that of the parent material, but a region of higher crystallinity was observed in the parent material adjacent to the weld, as a result of annealing.

The amorphous phase orientation was essentially unaffected by welding, but there was a significant increase in crystalline phase orientation.

Welding times between 2.5 and 7 seconds had little effect on tensile strength, which was around 75% of that of the parent material.

Morphological examination showed that the width of the weld region containing flow lines increased as the welding time increased, at the expense of the central nonspherulitic weld region.

Reference: Stevens SM: Characterisation of nylon 6,6 vibration welds. ANTEC 1997, Conference proceedings, Society of Plastics Engineers, Toronto, May 1997.

Allied Signal: Capron (material composition: 33% glass fiber reinforcement)

For nylon 66 with 33% glass-fiber reinforcement, the tensile strength of butt-welded joints under optimized welding conditions (maximum clamp load: 4.5 kN (1010 lbf); weld amplitude: 1.02–1.80 mm (0.04–0.07 inches); weld time: 4–25 seconds; weld frequency: 240 Hz) was 81.9 MPa (11,878 psi). This weld strength represents a 12% increase over the nonreinforced material. Examination of the morphology of the welded joint showed that in this case, the weld zone is "diffused" and not well-defined. It is suspected that the state of the resin matrix may play a bigger role than the fiber orientation.

Reference: Kagan V, Lui S, Smith GR: The optimized performance of linear vibration welded nylon 6 and nylon 66 butt joint. ANTEC 1996, Conference proceedings, Society of Plastics Engineers, Indianapolis, May 1996.

25.3.4 Spin Welding

Nylon 66

The following characteristic properties of polyamides have a major influence on the individual process phases of spin welding:

- Elastic modulus
- High crystalline melting point
- Abrupt transition to a low-viscosity melt
- Fillers and reinforcing materials
- Water absorption.

In the solid-friction phase, the conversion of the energy into heat is helped by the high rigidity achieved through the geometry of the part and through the inherent rigidity of the material. Because of the high melt enthalpy of these materials, high friction is needed to achieve the melting temperature.

Unsteady melt film formation is characterized by a sudden transition to the low-viscosity melt. Depending on the process parameters chosen, the transition to steady-state melt conditions occurs after a very short time. This point defines the most favorable welding time. Additional frictional energy can reduce the weld strength.

Throughout the joining process, absorbed water shows up in the form of bubbles in the weld bead. In the cooling or holding phase, in which only a slow squeeze flow prevails, the strength may be adversely affected under unfavorable conditions.

A critical energy level is required to achieve maximum strength. Exceeding this energy level is not expected to increase the joint strength. In fact, the quality of the joined parts is likely to diminish as a result of excess bead formation; a decrease in strength may also result from material degradation.

Reference: Potente H, Uebbing M: Friction welding of polyamides. *Polymer Engineering and Science*, 37(4), April 1997.

Nylon 66 (reinforcement: glass fiber)

In unreinforced polyamide, the welding factor (strength of weld/strength of bulk material) did not reach above 0.2, irrespective of pressure and speed. The low viscosity of polyamide leads to a very low melt layer thickness and very rapid cooling: the braking time was not short enough. High speeds (5–6 m/s; 16–20 ft/s) achieved a welding factor of 0.7 with glass-filled polyamide.

Reference: Tappe P, Potente H: New findings in the spin welding of plastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

25.3.5 Laser Welding

Nylon 66 (form: woven fabric)

Table 25.7 lists the results of mechanical testing of a range of lap joints made on a selection of woven fabrics manufactured from nylon 66. The welds were made with a Nd:YAG laser focused to a 7 mm (0.275 inch) diameter spot at powers between 50 and 100 W. The welding speeds were in the range 500–1000 mm/minute (20–40 inches/minute). The peel and lap shear tests were performed on 25 mm (1 inch) wide samples at a test rate of 5 mm/minute (0.2 inches/minute). The test results are quoted as the maximum applied force per mm of seam. Each result is an average of three tests. It can be seen that as a percentage of the strength of the parent materials, values between 25 and 40% were obtained for the welded joints in a simple lap configuration.

Reference: Hilton P, Jones I, Sallavanti R, Frieder LP: Welding fabrics. *Industrial Laser Solutions*, 16(6), p.15, June 2001.

25.3.6 Induction Welding

DuPont: Nylon 66 (features: unreinforced)

In this study, the induction welding system operated at 6.65 MHz. The heating element was made using metallic fillers mixed with nylon resin, and was sandwiched between two nylon plates and placed between the heating coils. The heating coil used in this study was a composite coil that contained a hair-pin coil with a 600 mm (23.6 inch) long, 25 mm (1 inch) wide copper plate and a water-cooled 6.35 × 6.35 mm (0.25 × 0.25 inch) square copper tube. A three-factor (heating time, weld pressure, and power level), two-level full factorial design of experiments was used to evaluate the lap shear strength.

It was found that weld time was the most dominant factor in affecting the weld strength, followed by power and pressure. It was also found that the weld strength was proportional to the heating time at constant power and constant pressure. In addition, final sample thickness was inversely proportional to the lap shear strength. Bending of the joint during testing was the major failure mode.

Reference: Wu CY, Agosto B: Implant induction welding of nylon 6/6. ANTEC 2005, Conference proceedings, Society of Plastics Engineers, Boston, May 2005.

25.3.7 Microwave Welding

Nylon 66

Single mode microwave welding of nylon 6/6 using conductive polyaniline (PANI) film was investigated. The reheatability of the film has been demonstrated which has potential in recycling applications. Higher PANI concentration in the film provides faster heating rates and achieves higher temperatures. Nylon 6/6 has the ability to absorb the microwave energy and raise its temperature causing thermal run away; therefore, time and/or power control is important in the welding of nylon 6/6 using microwave energy. Increasing the heating time without over-heating the sample increases the joint strength. Increasing the PANI concentration in the film increases the joint strength. The best joint strength, using 17.72% PANI in a 0.013 mm (0.0005 inch) thick film and 10 seconds of heating at 2000 W under 1 MPa (145 psi) joining pressure, was 71.45 ±

Table 25.7. Results of Mechanical Testing on a Range of Woven Fabrics Manufactured from Nylon 66

Material Color	Thickness, mm	Peel Strength, N/mm	Lap Shear Strength, N/mm	Parent Strength, N/mm
Brown	0.19	0.70	2.08	8.47
Orange	0.23	2.16	5.22	13.95
Bronze	0.16	2.07	2.76	9.38
Yellow	0.41	4.40	6.79	16.12

2.64 MPa (10,363 ± 383 psi). This is 97% of the bulk material strength. Power level is one of the important parameters when using high-conducting film in microwave welding. It seems that different concentrations and film thicknesses can reach full joint strength by careful control of the power level and heating time.

Reference: Wu CY, Staicovici S, Benatar A: Single mode microwave welding of nylon 6/6 using conductive polyaniline films. ANTEC 1996, Conference proceedings, Society of Plastics Engineers, Indianapolis, May 1996.

25.3.8 Mechanical Fastening

DuPont: Zytel GRZ (reinforcement: glass fiber)

Because of its good flow characteristics, glass reinforced Zytel (GRZ) can be used in a part with molded-in threads.

If molded-in threads are not feasible, another method of assembly is self-tapping screws. The screws cut their own thread as they are inserted into the plastic. Thread-cutting and thread-forming screws can be used.

Reference: *Dupont Glass-Reinforced Zytel Nylon Resin*, Supplier Technical Report (E-22693), DuPont, 1993.

25.4 Nylon 612

25.4.1 Ultrasonic Welding

DuPont: Zytel 151

Due to low dry-as-molded stiffness, parts molded of Zytel 151 and other 612 nylons can be welded, but with slightly more difficulty than Zytel 101. These resins are noted for their very low moisture absorption. Therefore, in all but the most critical applications, it is not necessary to keep the parts dry before welding.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I*, Supplier design guide, DuPont Company, 2002.

DuPont: Zytel 77G (reinforcement: glass fiber)

Because of the glass fibers, glass reinforced Zytel (GRZ) may need more weld area than unreinforced Zytel. Also, the plastic should be dry as molded since moisture degrades weld strength.

Reference: *Dupont Glass-Reinforced Zytel Nylon Resin*, Supplier Technical Report (E-22693), DuPont, 1993.

25.5 Nylon 46

25.5.1 Adhesive Bonding

DSM Engineering Plastics: Stanyl TW300 (features: unreinforced); **Stanyl TW200-76** (reinforcement: glass fiber)

The adhesives used in this study were: PLUS CP792 (a cyanoacrylate by Permabond), Araldite AW106 + HV953V hardener (two-part epoxy by Ciba Speciality Chemicals) and AF163-2K (a modified epoxy film by 3M).

Trials were performed using three excimer lasers: XeCl (wavelength 308 nm), ArF (wavelength 193 nm), and KrF (wavelength 248 nm). The pulse energy of the XeCl laser was120 mJ and, for both ArF and KrF lasers, it was 100 mJ, with a pulse duration of 10–15 ns. The beams were focused through a 500 mm (19.7 inch) focal length mirror to produce a rectangular area of 6 × 3 mm (0.24 × 0.12 inches) on the adherend. For each specimen, a treated width of approximately 25 mm (1 inch) was produced.

Results of this work have shown that the ArF laser was very effective in increasing the joint strength of both unreinforced and glass-fiber reinforced polyamide 4,6. For unreinforced polyamide, most joints failed cohesively within the adherend.

Reference: Tavakoli SM, Riches ST: Laser surface modification of polymers to enhance adhesion. Part II—PEEK, APC-2, LCP and PA. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

25.6 Nylon 11

25.6.1 Heated Tool Welding

Nylon 11 (form: pipe)

The parameters shown in Table 25.8, were used throughout this study to prepare all of the heat-fused samples.

Six samples were heat-fused in wet/wet, dry/dry, wet/dry type configurations from a single lot of pipe. Tensile properties were obtained using the method

Table 25.8. Butt Heat Fusion Operating Parameters for PA11

Heater temperature	500°F (260°C)
Heating (soak) time	60–75 seconds
Interface pressure	50–100 psi (0.34–0.69 MPa)

described in ASTM D638. The specimens were tested with the beads intact.

The results indicated that there was no significant adverse effect in the tensile properties at yield attributed to the varying moisture contents as compared to the control pipe.

Reference: Patadia H, Pitzi TJ, Kanninen M F, Mamoun MM: An evaluation of polyamide 11 for use in high pressure/high temperature gas piping systems. Plastics Piping Systems for Gas Distribution, Conference proceedings, October 1997.

25.7 Nylon 12

25.7.1 General

Degussa: Vestamid

All established types of welding technologies can be applied to Vestamid; typical technologies used are hot plate welding, ultrasonic welding, friction welding (by rotation or vibration), high frequency welding, and laser welding.

Reference: *Handling and Processing of Vestamid*, Supplier design guide (03/lau/500e), Degussa AG, 2003.

EMS-Chemie: Grilamid

All welding methods developed for engineering plastics can be used to weld Grilamid. High frequency and impulse welding are used for welding films. Very good bonds can be obtained on shaped articles made of Grilamid using heated tool welding, ultrasonic welding, spin welding, laser welding, and vibration welding methods.

When using ultrasonic welding, glass-bead or glass-fiber reinforced products (e.g., Grilamid LKN-5H, Grilamid LV-3H) can be welded very successfully. It is practically impossible to weld Grilamid grades containing plasticizers (e.g., Grilamid L25W40) using ultrasonic welding.

Vibration welding presents the possibility of welding glass-fiber reinforced Grilamid and amorphous, transparent Grilamid TR55.

Parts made of Grilamid can be fastened successfully using screws which form their own threads (self-tapping and thread-cutting screws).

Reference: *Grilamid Polyamide 12*, Supplier design guide, EMS-Chemie.

EMS-Chemie: Grilamid TR55 (features: transparent); **Grilamid TR55FC** (features: high impact, transparent, chemical resistant); **Grilamid TR55LX** (features: high impact, UV stabilized, transparent); **Grilamid TR55LY** (features: high impact, UV stabilized, transparent); **Grilamid TR55UV** (features: UV stabilized, transparent)

Ultrasonic welding, vibration welding, and impulse welding are all suitable for joining Grilamid TR55, TR55UV, TR55LX, TR55LY, and TR55FC parts. When welding, the surfaces to be joined need only be melted and rapidly pressed together. It is also possible to insert metal parts ultrasonically. Parts which are not being welded within a few hours of molding should be stored in moisture-proof packaging to insure adhesion when being assembled later.

Reference: *Grilamid TR55 Transparent Nylons,* Supplier design guide (GR1-104), EMS-Chemie.

25.7.2 Heated Tool Welding

Nylon 12 (form: pipe)

Butt fusion samples were produced to evaluate the effect of heat-soak time and interfacial pressure on the quality of butt fusion joints of polyamide 12 pipe. Samples were prepared using a heater plate temperature of 260°C (500°F), torque hold times of 60 seconds, and a cooling period of 10 minutes. The applied torque during fusion was varied between 10 and 20 ft-lbs (13.6–27.1 Nm). The heat soak time under pressure varied between 60 and 90 seconds.

The average pressure to failure for quick burst testing according to ASTM D1599 was 1460 psi (10 MPa), which relates to a hoop stress of 7230 psi (50 MPa). All failures were outside of the fusion joint area and failed in a ductile fashion. All short-term tensile properties, when tested as per ASTM D638, were consistent with the properties of unfused pipe. Samples were submitted to test for long-term hydrostatic strength at 80°C (176°F) and a pressure of 290 psig (20 bar). No failures were observed after 1000 hours of testing.

Reference: Wolf R, Yoshifumi Y, Nakamura K, Patadia H: An evaluation of polyamide 12 for high pressure natural gas distribution applications. Plastics Pipes XIII, Conference proceedings, Washingon DC, October 2006.

25.7.3 Solvent Welding

Degussa: Vestamid

With solvent welding, using for example, m-cresol, phenol with methanol, or resorcine with methanol, a good bond strength can be reached.

Reference: *Handling and Processing of Vestamid*, Supplier design guide (03/lau/500e), Degussa AG, 2003.

EMS-Chemie: Grilamid TR55 (features: transparent); **Grilamid TR55LX** (features: high impact, UV stabilized, transparent); **Grilamid TR55LY** (features: high impact, UV stabilized, transparent); **Grilamid TR55UV** (features: UV stabilized, transparent)

Grilamid TR55 to Grilamid TR55 (or TR55UV to TR55UV) can be joined by the use of the following solvents: formic acid, resorcinol, cresol, isopropanol, butanol, and resorcinol—ethanol solution (2:3 mix).

Reference: *Grilamid TR55 Transparent Nylons*, Supplier design guide (GR1-104), EMS-Chemie.

25.7.4 Adhesive Bonding

Degussa: Vestamid

Vestamid can be bonded using commercially available adhesives based on:

- Epoxies: one- or two-pack adhesives (gap filling), suitable for larger adherent surfaces. Hot setting adhesives reduce clamping time and may increase adhesion strength.
- Polyurethane: one- or two-pack and (reactive) hot melt adhesives (gap filling, flexible adhesives mostly with longer pot life and clamping time), suitable for larger adherent surfaces.
- Cyanoacrylates: one-pack adhesives (short setting time), suitable for small glue-lines and adherent surfaces.

Reference: *Handling and Processing of Vestamid*, Supplier design guide (03/lau/500e), Degussa AG, 2003.

EMS-Chemie: Grilamid

Grilamid's excellent resistance to chemicals and non-polar structure makes it a difficult material to bond. However, using the right methods and a suitable adhesive, technical bonding is possible.

Cyanoacrylate and acrylate single-component adhesives are particularly suited for bonding Grilamid to metal. Polyurethane and epoxy resin two-component adhesives can also be used for bonding Grilamid. A significant improvement in bond quality can be achieved by pretreatment. Pretreatments include:

- Degreasing: use of organic solvents, such as acetone
- Mechanical removal: scrubbing, grinding or sand blasting
- Electro-chemical: corona discharge or low-pressure plasma
- Thermal: flame treatment
- Chemical: treatment with caustic substances

Reference: *Grilamid Polyamide 12*, Supplier design guide, EMS-Chemie.

25.8 Nylon 6/3T

25.8.1 General

Degussa: Trogamid (features: transparent)

All established types of welding technologies can be applied to Trogamid; typical technologies used are hot plate welding, ultrasonic welding, friction welding (spin or vibration), and high frequency welding.

Reference: *Trogamid Handling and Processing*, Supplier design guide (02/wi/1000/e), Degussa AG, 2002.

Huls AG: Trogamid (features: transparent)

Trogamid moldings can in principle be subjected to all known welding processes. For sufficient weld seam strength, the achievement of a correspondingly high melt temperature in the joint area from about 260–310°C (500–590°F) is important. Owing to its amorphous nature and its melt toughness, the temperature range is not as critical as in the semicrystalline polyamides. It is important that the parts to be welded are dry for which reason assembly as soon as possible after shaping is recommended. Otherwise, the moldings are to be dried beforehand, where drying times of up to one hour at 100–110°C (212–230°F) may be sufficient to remove the disturbing surface water.

Welding methods that can be considered are heated tool welding, vibration and spin welding, and ultrasonic welding. The heating or welding times as well as the joining pressure are part dependent, and must therefore be determined empirically.

Reference: *Huls Trogamid Polyamide 6-3-T*, Supplier design guide (42.01.027e), Huls Aktiengesellschaft, 1992.

25.8.2 Ultrasonic Welding

Huls AG: Trogamid (features: transparent)

In the ultrasonic welding process, close-and far-range welding are possible. Trogamid can be combined with Vestamid by ultrasonic welding. For good welding results in series manufacture, the observance of small dimensional tolerances in the joint area is very important. For directed energy transfer by the sonotrode, the execution of the joint plane in the form of a pinch-off weld or the use of an energy direction transmitter has proven worthwhile.

Reference: *Huls Trogamid Polyamide 6-3-T*, Supplier design guide (42.01.027e), Huls Aktiengesellschaft, 1992.

25.8.3 Solvent Welding

Huls AG: Trogamid (features: transparent)

For solvent bonding, dimethyl formamide (DMF) and concentrated formic acid can be used as solvents. Trogamid (10–20%) dissolved in these solvents has a crack-filling effect in uneven joint faces. Such solutions can only bond Trogamid with itself. With good bonding face pretreatment, tensile shear strengths of 20 MPa (2900 psi) are achieved.

Reference: *Huls Trogamid Polyamide 6-3-T*, Supplier design guide (42.01.027e), Huls Aktiengesellschaft, 1992.

25.8.4 Adhesive Bonding

Degussa: Trogamid (features: transparent)

Trogamid can be bonded using commercially available adhesives based on:

- Polyurethanes: one- or two-pack and (reactive) hot-melt adhesives (gap filling, flexible adhesives mostly with longer pot life and clamping time), suitable for larger adherent surfaces.
- Cyanoacrylates: one-pack adhesives (short setting time), suitable for small gluelines and adherent surfaces.
- Epoxies: one- or two-pack adhesives (gap filling), better results at elevated temperatures.

Reference: *Trogamid Handling and Processing*, Supplier design guide (02/wi/1000/e), Degussa AG, 2002.

Huls AG: Trogamid (features: transparent)

Bonding of Trogamid moldings with each other and with other materials, for example, metals, is possible if suitable adhesives are used. In particular, an improvement of the bond seam strength is achieved by scouring the joint faces (granularity 240) and subsequent degreasing. The joining pressure should be so dimensioned that an adhesive bonding film is preserved between the bonding surfaces. In laboratory tests, a joining pressure of approximately 1 MPa (145 psi) has been found to be beneficial.

Reference: *Huls Trogamid Polyamide 6-3-T*, Supplier design guide (42.01.027e), Huls Aktiengesellschaft, 1992.

25.9 Polyphthalamide

25.9.1 General

Amoco Performance Products: Amodel AS1133HS (material composition: 33% glass-fiber reinforcement)

Components produced from Amodel resins can be readily joined using hot plate, vibration, spin, or ultrasonic welding.

Acceptable welds can be achieved using all these welding techniques. Ultrasonic welding does require near-field energy appplication for strong welds. In general, absorbed moisture does not interfere with welding, but best results are obtained using samples that contain "normal" amounts of moisture (1.8%) or less.

Reference: *Amodel PPA Resins Engineering Data*, Supplier design guide (AM-F-50060), Amoco Performance Products, Inc.

25.9.2 Heated Tool Welding

Solvay Advanced Polymers: Amodel AS1133HS (material composition: 33% glass fiber reinforcement)

Tests were conducted to determine the hot plate welding characteristics of Amodel polyphthalamide. The specimens used were bars 4 inches (102 mm) long, 1 inch (25 mm) wide, and 0.25 inches (6 mm) thick. The welding machine was set up to provide a nominal lap shear weld of 0.5 by 1 inch (13 by 25 mm).

Best results were obtained using a hot plate temperature of 626°F (330°C), a clamping pressure of 30 psi (207 kPa), a welding time of 40 seconds, and a hold time of 20 seconds. The strength of the bond produced was comparable to the strength of the material itself, that is, the majority of the specimens failed at points other than the joint during mechanical testing.

Test plaques occasionally stuck to the hot plate, unless a silicone mold release was applied, and the hot plate allowed to return to thermal equilibrium. Tests showed that the use of mold release did not reduce weld strength. Absorbed moisture did not significantly affect weld strength at dry (0%) and normal (1.8%) levels, but it did reduce weld strength at the saturated (3.8%) condition.

Reference: *Amodel polyphthalamide Design Guide*, Supplier design guide (AM-50477), Solvay Advanced Polymers, 2002.

25.9.3 Ultrasonic Welding

Solvay Advanced Polymers: Amodel AS1133HS (material composition: 33% glass-fiber reinforcement)

The ultrasonic welding machine used to weld Amodel AS-1133 HS resin was microprocessor controlled. With this unit, it is possible to dial in the amount of energy that will be applied to the sample. The samples used were injection-molded cups. Aluminum fixturing held the parts in a butt joint configuration.

Welds produced using a near field horn-to-joint distance, defined as 6 mm (1/4 inch) or less, were excellent. Welds made using the far field horn position were weak (1/3 of the strength achieved at near field) and are probably not useful. The conditions that gave acceptable strength were weld energy of 750 J and pressure of 617 psi (4.3 MPa).

Reference: *Amodel Polyphthalamide Design Guide*, Supplier design guide (AM-50477), Solvay Advanced Polymers, 2002.

25.9.4 Vibration Welding

Solvay Advanced Polymers: Amodel AS1133HS (material composition: 33% glass-fiber reinforcement)

The vibration welding machine used to weld Amodel AS1133HS resin operated at a nominal frequency of 240 Hz. The specimens used were 4 inches (102 mm) long, by 1 inch (25 mm) wide by 0.25 inches (6 mm) thick, and they were welded in a 1 by 0.5 inch (25 by 13 mm) lap shear configuration.

This method was very effective, and welds as strong as the parent material were easily obtained. This technique proved relatively insensitive to welding conditions, giving good results at weld times as short as 0.6 seconds and pressures as low as 320 psi (2.2 MPa). Best results were obtained using specimens containing a normal (1.8%) amount of moisture.

Reference: *Amodel Polyphthalamide Design Guide*, Supplier design guide (AM-50477), Solvay Advanced Polymers, 2002.

Solvay Advanced Polymers: Amodel A-1133 (reinforcement: 33% glass fibers); **Amodel A-1340** (reinforcement: 15% glass fibers, 25% mineral); **Amodel AS-4133** (reinforcement: 33% glass fibers)

A T-weld geometry was studied. The materials used were nylon 6, nylon 66, and polyphthalamide (all glass-fiber reinforced).

The welding parameters were:

- Frequency: 230 Hz (approximate)
- Weld pressure: 2.2 MPa (319 psi)
- Amplitude: 1.8 mm (0.07 inches)
- Weld time: 3 seconds
- Hold time: 3 seconds

All the trials demonstrated that when there is a melt temperature difference between the materials, the weld depth is primarily achieved by the melting and consequent erosion of the material with the lower melt temperature. The best welds were generally obtained when the melt temperatures were the same or similar, and the worst welds were obtained when the melt temperature difference was the greatest.

For the heterogeneous welds on materials containing long glass fibers, where the melt temperature differences between the materials being welded ranged from 15 to 72°C (27 to 130°F), the weld strengths barely varied.

This data showed that it should be possible to get good welds between PA6 (and PA66) and PPA.

Reference: LeBlanc V, Baylis B, Qi L, Watt D: Vibration welding of dissimilar nylons. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

25.9.5 Spin Welding

Solvay Advanced Polymers: Amodel AS1133HS (material composition: 33% glass-fiber reinforcement)

The spin welding machine used to weld Amodel AS-1133 HS resin was an inertia-type, where the energy available for spinning the sample is limited to that stored in a flywheel.

The specimens used for spin welding were injection-molded cups. This style has an interference joint configuration. Excellent weld strength was obtained using this method.

Because welding condition settings are machine specific, they are not generally useful in setting a starting point. Rather, it was observed that as forge pressure and angular velocity were increased, weld strength increased up to a maximum, and then decreased when an excessive amount of either pressure or velocity was applied. The explanation for this observation is that when a weld was made with too high a forge pressure, the spinning motion was stopped nearly instantaneously, and not enough polymer melted and flowed. At the other extreme, a high angular velocity and a low forge pressure, the top part essentially sat on top of the bottom part and freely rotated without being forged into the interference fit. Thus, to assure a good joint, a suitable welding condition must be found so that both melting and forging occurs.

Moisture content did not significantly affect weld strength.

Reference: *Amodel Polyphthalamide Design Guide*, Supplier design guide (AM-50477), Solvay Advanced Polymers, 2002.

25.9.6 Adhesive Bonding

Solvay Advanced Polymers: Amodel AS1133HS (material composition: 33% glass-fiber reinforcement)

Injection molded samples of Amodel A-1133 HS resin were bonded with both an epoxy and a urethane adhesive. The epoxy was a two-part adhesive, sold under the trade name Lord 305-1/-2 and the urethane was a two-part system known as Lord 7500 A.

To prepare the test specimens for the Lord 305-1/-2, a cure cycle of 30 minutes at 120°C (250°F) followed by conditioning at room temperature for 72 hours was employed. The cure cycle for the Lord 7500 A adhesive was 10 minutes at 90°C (200°F) followed by conditioning at room temperature for 72 hours.

Bond strengths were tested at low temperature, room temperature, and an elevated temperature. To evaluate the effect of humid aging, specimens were conditioned for 14 days at 38°C (100°F), and 100% relative humidity. Some specimens were tested immediately after conditioning; others were tested 24 hours after conditioning.

Impact performance was determined with a side impact tester according to GM specification #9751P. Lap shear values were measured on an Instron testing machine, using a pull rate of 0.5 inches/minute (13 mm/min) according to ASTM D 1002. The results are given in Figs. 25.1 and 25.2. In general, the epoxy adhesive performed slightly better than the urethane. Acrylic adhesives are not recommended for use with Amodel resins.

Reference: *Amodel Polyphthalamide Design Guide*, Supplier design guide (AM-50477), Solvay Advanced Polymers, 2002.

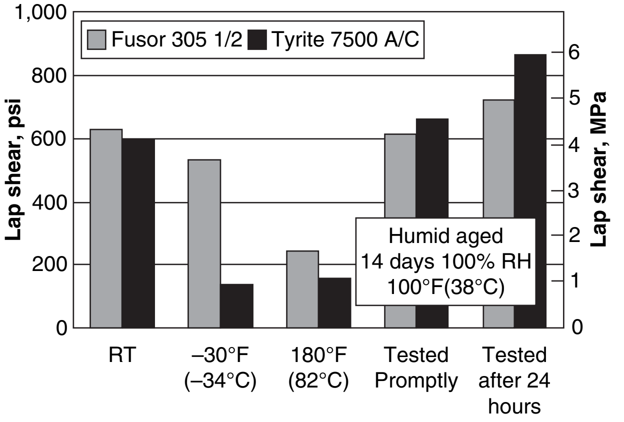


Figure 25.1. Lap shear bond strengths for Amodel AS1133HS 33% glass-fiber reinforced PPA resin.

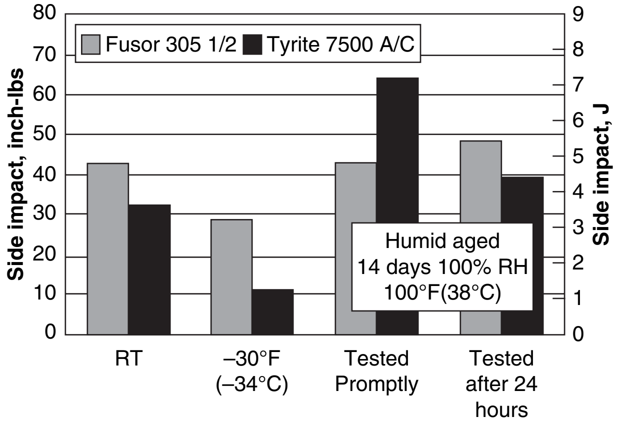


Figure 25.2. Side impact bond strengths for Amodel AS1133HS 33% glass-fiber reinforced PPA resin.

25.9.7 Mechanical Fastening

Solvay Advanced Polymers: Amodel A1230L (material composition: 30% mineral filler); **Amodel AS1133HS** (material composition: 33% glass-fiber reinforcement); **Amodel ET1000HS** (features: lubricated, impact modified, heat stabilized)

Snap-fit Assemblies: The maximum strain recommendations for cantilever snap-fits are given in Table 25.9.

Reference: *Amodel Polyphthalamide Design Guide*, Supplier design guide (AM-50477), Solvay Advanced Polymers, 2002.

Table 25.9. Maximum Strain Recommendations for Cantilever Snap-fits Made from Several Grades of Amodel Resins

Amodel PPA Grade	Maximum Strain, %
ET-1000HS	1.0
A-1230L	0.5
AS-1133HS	1.0

Amoco Performance Products: Amodel AS1133HS (material composition: 33% glass-fiber reinforcement)

Threaded Fasteners: When threaded metal fasteners are used to retain or secure plastic parts to an assembly, and the assembly is subjected to changes in temperature, the difference between the thermal expansion coefficients of the metal and the plastic can cause problems. When a threaded fastener is tightened, the fastener is elongated slightly, and a compressive stress is generated on the substrate. This compressive stress maintains the tightness of the bolt.

When the assembly is heated, both the plastic part and the metal fastener will expand. The plastic part, however, is constrained by the metal fastener, and cannot expand. This results in increased compressive stresses in the plastic and a corresponding increased tendency for compressive creep or stress relaxation to occur. The relaxation of the compressive stress will result in reduced torque retention in the bolts.

The coefficient of thermal expansion of Amodel resin is lower than those of nylon 66 or nylon 46, and therefore closer to that of the steel. The smaller difference in thermal expansion results in lower induced stress due to the compressive strain caused by the thermal excursion in the constrained part. This translates to lower creep and therefore better torque retention for such bolted assemblies.

Threaded Inserts: Figure 25.3 depicts the recommended insert and boss designs for use with Amodel PPA resin.

Reference: *Amodel PPA Resins Engineering Data*, Supplier design guide (AM-F-50060), Amoco Performance Products, Inc.

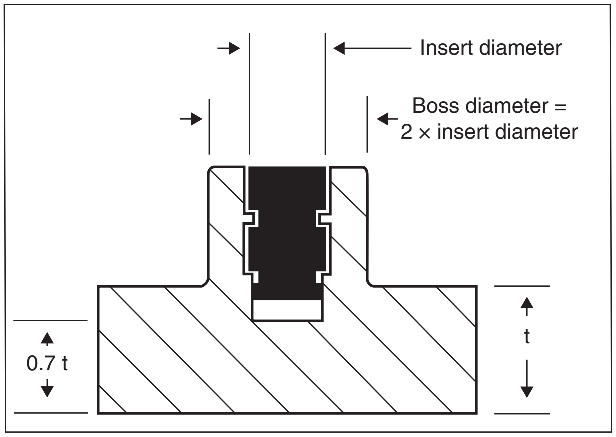


Figure 25.3. Boss design for ultrasonic inserts in Amodel PPA resin.

25.10 Polyarylamide

25.10.1 Ultrasonic Welding

Solvay: Ixef 1002; Ixef 1022 (material composition: 50% glass-fiber reinforcement)

IXEF compounds are more rigid than the other reinforced thermoplastics; as a result, the vibrational energy is transmitted more easily through the molded parts, and the quality of the weld is correspondingly higher.

Ultrasonic welds were made in Ixef compounds, using the conditions given here:

- Frequency: 18 kHz
- Power: 1.2 kW maximum
- Welding time: 0.8 seconds
- Holding time: 0.25–5 seconds
- Force applied on the sonotrode: 580 N (130 lbf)

The results of the shear tests are given in Table 25.10.

Reference: *IXEF Polyarylamide Design & Molding Guide*, Supplier design guide (Br 1563c-B-6-0901), Solvay Advanced Polymers, 2000.

Table 25.10. Resistance of Shearing of Ultrasonically Welding Joints in Ixef Polyarylamide

Ixef grade	Breaking Strength Under a Shear Force, MPa (psi)
1002	26 (3770)
1022	19 (2760)
1501	19 (2760)

25.10.2 Adhesive Bonding

Solvay: Ixef

The IXEF compounds can be assembled by bonding without any difficulty. Four main types of adhesives have been evaluated for bonding IXEF on IXEF and IXEF on steel:

- Cyanoacrylates: single part fast curing adhesives, ideally suited for small part bonding; toughened grades available; optimum gap fill ≤ 0.15 mm (0.006 inches); maximum temperature 80–110°C (176–230°F) (depending on grade).
- Two-part acrylics: tough and semiflexible; good adhesion to many substrates; optimum gap fill ≤ 1 mm (0.04 inches); maximum temperature 100–120°C (212–248°F) (depending on grade).
- Modified silane adhesive/sealants: very flexible; slow cure; excellent gap fill (3–4 mm; 0.12–0.16 inches); good water resistance.
- Epoxies: good shear and impact resistance; optimum gap fill ≤ 2 mm (0.08 inches); maximum temperature 100°C (212°F).

Table 25.11 presents the shear strength results for various bonding tests and adhesives.

Reference: *IXEF Polyarylamide Design & Molding Guide*, Supplier design guide (Br 1563c-B-6-0901), Solvay Advanced Polymers, 2000.

25.10.3 Mechanical Fastening

Solvay: Ixef

Screw Assembly: The maximum tightening torque that an IXEF polyarylamide plate can withstand and the extraction force which a screw can resist are outlined in Table 25.12.

Reference: *IXEF Polyarylamide Design & Molding Guide*, Supplier design guide (Br 1563c-B-6-0901), Solvay Advanced Polymers, 2000.

Table 25.11. Results of Bonding Tests (IXEF/IXEF and IXEF/steel)

Adhesive		Cure Speed	Typical Tensile Shear Strength, N/mm^2			
			IXEF 1022/IXEF 1022		IXEF 1022/steel	
			As Received[b]	Abraded[c]	As Received[b]	Abraded[c]
Cyanoacrylate	Loctite 406	5–20 seconds	4–6	5–8	Not recommended	5–7
Toughened cyanoacrylate	Loctite 480	20–80 seconds	3–7	8–10[a]	3–6	7–10[a]
Two part acrylic	Loctite 3295	10–30 minutes	3–5	3–6	3–5	4–7
Two part acrylic	Dexter H3101	8–20 minutes	2–4	2–5	2–4	3–5
Epoxy	Loctite 3425	1.5 hour	3–6	4–7	3–6	4–6
Modified silane adhesive/sealant	Loctite 5069	3.5 mm/24 hour (skin over 30 minutes)	2–4	2–4	2–4	2–4

[a] Substrate failure of IXEF.

[b] Surface finish 1–2 Ra.

[c] Abraded with 60 grit paper (4–5 Ra).

Table 25.12. Screw Assembly in an IXEF Polyarylamide Part

Screw type	Diameter of Hole, mm	Maximum Torque, Nm	Extraction Force, kN
M 2.6 × 0.45	2.2	>1.0	>1.7
M 3.0 × 0.5	2.5	>1.5	>3.6
M 4.0 × 0.7	3.4	>4.5	4.6
M 5.0 × 0.8	4.3	7.5	6.1
M 6.0 × 1.0	5.1	>6.5	7.7

Solvay: IXEF 1022 (material composition: 50% glass fiber reinforcement)

The coefficient of thermal expansion of IXEF compounds is similar to that of metals, so it is possible for mechanical assemblies to retain the same dimensions over a wide temperature range.

Snap-fit Assemblies: As IXEF 1022 grade is very rigid and its elongation at break is 1.7%, snap-fit assembly is not advisable without studying the geometry of the clip.

Threaded Inserts: Various types of metal inserts can be used for assembling IXEF parts:

- Inserts fixed by ultrasonics
- Inserts fixed by pressing
- Inserts placed in the mold
- Ring inserts

If the insert is to be fixed by ultrasonics, it is necessary to follow the instructions given by the producer of the equipment. If there are no instructions, it is suggested the following conditions be tried:

$$D = d - 0.6 \text{ mm } (0.024 \text{ inches})$$

where D = external diameter of the insert, d = diameter of the hole.

Reference: *IXEF Reinforced Polyarylamide Based Thermoplastic Compounds Technical Manual*, Supplier design guide (Br 1409c-B-2-1190), Solvay, 1990.

26 Polyamide-imide

26.1 Adhesive Bonding

Solvay Advanced Polymers: Torlon

Torlon poly(amide-imide) parts can be joined with commercial adhesives, extending design options. A variety of adhesives including amide-imide, epoxy and cyanoacrylate can be used to bond Torlon parts. Cyanoacrylates have poor environmental resistance and are not recommended. Silicone, acrylic, and urethane adhesives are generally not recommended unless environment conditions preclude other options. The amide-imide adhesive is made by dissolving 35 parts of Torlon 4000T PAI powder in 65 parts of *N*-methylpyrrolidone (NMP). It should be noted that NMP is a flammable organic solvent and the appropriate handling procedures recommended by EPA, NIOSH and OSHA should be followed.

Torlon 4203L, 5030, and 7130 are relatively easy to bond. Bearing grades 4301, 4275, and 4435 have inherent lubricity, and are more difficult to bond. Table 26.1 compares the shear strengths of these grades bonded with epoxy, cyanoacrylate and amide-imide adhesives.

Bonding surfaces should be free of contaminants, such as oil, hydraulic fluid, and dust. Torlon parts should be dried for at least 24 hours at 300°F (149°C) in a desiccant oven to dispel casual moisture prior to bonding; thicker parts, over 0.25 inches (6.3 mm), require longer drying time. Torlon surfaces should be mechanically abraded and solvent-wiped, or treated with a plasma arc to enhance adhesion.

For adhesives other than amide-imide, follow the manufacturer's directions. For amide-imide adhesive: coat each of the mating surfaces with a thin, uniform film of the adhesive. Adhesive-coated surfaces should be clamped under minimal pressure, approximately 0.25 psi (1.7 kPa). The excess adhesive can be cleaned with NMP.

Amide-imide adhesive should be cured in a vented, air-circulating oven. The recommended cycle is 24 hours at 73°F (23°C), 24 hours at 300°F (149°C), 2 hours at 400°F (204°C). The parts should remain clamped, until cooled to below 150°F (66°C).

Reference: *Torlon Polyamide-imide Design Guide*, Supplier design guide (T-50246), Solvay Advanced Polymers, 2003.

Amoco Performance Products: Torlon 4203L (material composition: 0.5% fluorocarbon, 3% TiO_2); **Torlon 4275** (features: wear resistant; material composition: 3% fluorocarbon, 30% graphite powder); **Torlon 4301** (features: wear resistant; material composition: 20% graphite powder, 3% fluorocarbon); **Torlon 5030** (material composition: 1% fluorocarbon, 30% glass fiber reinforcement); **Torlon 7130** (features: fatigue resistant; material composition: 1% fluorocarbon, 30% graphite); **Torlon 9040** (material composition: 1% fluorocarbon, 40% glass fiber reinforcement)

The impact strengths of bonded Torlon 4203L specimens using the ASTM D256 (Izod impact) apparatus

Table 26.1. Shear Strength of Torlon PAI to Torlon PAI Bonds

PAI grade	Epoxy[a]		Cyanoacrylate[b]		Amide-imide	
	psi	MPa	psi	MPa	psi	MPa
Torlon 4203L	6000+	41.4	2780	19.2	5000+	34.5
Torlon 4301	2250	15.5	1740	12.0	2890	19.9
Torlon 4275	3500	24.1	1680	11.6	3400	23.4
Torlon 5030	4780	33.0	3070	21.2	5140	35.4
Torlon 7130	6400+	44.1	3980	27.4	4750	32.8

[a] Hysol EA 9330 from Dexter Corporation.
[b] CA 5000 from Lord Corporation.

were measured in foot-pounds of force required to break the bond. Epoxy bonds failed at impacts ranging from 0.6 to 14.6; amide-imide specimens failed at 8.3 to 20+.

Amide-imide adhesive provides high strength bonds at elevated temperature. At 350°F (177°C), amide-imide adhesive with 40% SCF withstands lap shear forces over 4000 psi (27.58 MPa) applied to Torlon 4203L/Torlon 4203L bonds. A high-temperature epoxy failed at 750 psi (5.17 MPa) under the same conditions.

Torlon and metal parts can be joined with adhesives. With proper surface preparation and adhesive handling, the resulting bonds will have high strength. In addition, there will be minimal stress at the interface with temperature change. This is because Torlon resins, unlike many other high temperature plastics, have expansion coefficients similar to those of metals.

Bond strength depends on adhesive selection and Torlon grade, as well as proper technique in preparing and curing the bond. Mechanical abrasion alone may not be adequate for preparing steel surfaces—chemical treatment of the steel is recommended when service temperature requires use of amide-imide adhesive.

References: *Torlon Engineering Polymers/Design Manual*, Supplier design guide (F-49893), Amoco Performance Products.

26.2 Mechanical Fastening

Solvay Advanced Polymers: Torlon

The dimensional stability and creep resistance of Torlon allows it to be readily joined with metal components even in rotating or sliding assemblies. Because postcured Torlon parts are extremely tough, some joining techniques will not be suitable.

Snap-fit Assemblies: Snap-fit is an economical and simple method of joining Torlon parts. Although the strain limit must be considered for a snap-fit assembly that will be repeatedly assembled and disassembled, Torlon engineering polymers are excellent for this type of use, due to their superior fatigue strength. The high modulus and elongation and low creep of Torlon resins also make them well suited for snap-fit designs. Snap-in fingers in the locked position should be strain-free, or under a level of stress that can be tolerated by the material. Torlon resins can tolerate up to 10% strain for unfilled grades, and 5% strain for filled grades. Graphite fiber reinforced grades are not suitable for snap-fit assembly.

Self-tapping Screws: In general, Torlon is too tough for self-tapping screws. Tapped holes are recommended.

Molded-in Inserts: Metal inserts can be molded into Torlon parts. Preheating the insert to the temperature of the mold is required for best results. While polyamide-imide has low shrinkage, it is still important to have sufficient material around the insert to distribute the stress induced by shrinkage.

Threaded Mechanical Inserts: Self-threading, self-locking inserts provide a high-strength, low-stress option for joining Torlon parts. These metal inserts have an exterior "locking" feature for anchorage in the Torlon part and allow for repeated assembly and disassembly through the threaded interior.

Molded-in Threads: Both external and internal threads can be molded with Torlon polymer to a Class-2 tolerance. Mating parts with metal fasteners in Torlon threads works well because the thermal expansion of Torlon PAI is close to that of metal, therefore, there will be relatively low thermal stress at the metal to plastic interface. Due to the increase in mold cost, it is generally advisable to machine threads for short runs.

Threaded Fasteners: Threaded fasteners molded from Torlon engineering polymers are dependable due to the high strength, modulus, and load-bearing characteristics of Torlon engineering polymers.

Press Fit Assemblies: Interference, or press fits provide joints with good strength at minimum cost. Torlon engineering polymer is ideal for this joining technique due to its resistance to creep. Diametral interference, actual service temperature, and load conditions should be evaluated to determine if stresses are within design limits.

Screw Holding Strength: Metal screws can securely join threaded Torlon parts. Holes for #4–40 screws were drilled and tapped in 4.8 mm (0.19 inch) thick Torlon plaques. Screw pull-out strength determined by ASTM D1761 are given in Table 26.2.

Ultrasonic Inserts: Metal inserts can be imbedded in uncured Torlon parts by ultrasonic insertion. Inserts are installed rapidly with strength comparable to that provided by molded-in techniques. A hole is molded slightly smaller than the insert. The metal insert is brought

Table 26.2. Screw Holding Strength of Threads in Torlon PAI

	Pull-Out Strength		Engagement
	lb	kg	Threads per hole
Torlon 4203L	540	240	7.5
Torlon 4275	400	180	7.7
Torlon 4301	460	200	7.8

in contact with the Torlon part. Vibration in excess of 18 kHz is applied to the metal insert, creating frictional heat which melts the plastic. High strength is achieved if sufficient plastic flows around knurls, threads, etc.

Reference: *Torlon Polyamide-imide Design Guide*, Supplier design guide (T-50246), Solvay Advanced Polymers, 2003.

Amoco Performance Products: Torlon

Expansion inserts are generally not recommended; however, each application should be considered on an individual basis.

Molded-in Inserts: Threads molded into Torlon parts have good pull-out strength, but if greater strength is needed, metal inserts can be molded in. Torlon resins have low coefficients of thermal expansion, making them excellent materials for applications integrating plastic and metal. For ease of molding, inserts should be situated perpendicular to the parting line, and should be supported so that they are not displaced during the injection of the molten plastic.

Reference: *Torlon Engineering Polymers/Design Manual*, Supplier design guide (F-49893), Amoco Performance Products.

27 Polycarbonate

27.1 General

Altuglas International: Tuffak (form: sheet)

Table 27.1 shows an overall comparison of joining methods for Tuffak polycarbonate sheet.

Reference: *Tuffak Polycarbonate Sheet. Forming and Fabrication*, Supplier design guide (ADV980496/APL:ATG-16S/web/6-00), Altuglas International, 2000.

Dow Chemical: Calibre (features: transparent)

Assembly methods for parts made of Calibre polycarbonate are numerous, ranging from relatively simple mechanical fits to complex welding operations. Calibre polycarbonates provide for superior solvent and adhesive bonding; their rigidity permits ultrasonic and vibration welding.

Each of the assembly methods used for parts of Calibre polycarbonate has its advantages and disadvantages. The decision of which method is best suited for a particular application should be based on several factors: product requirements, technical expertise, production requirements, equipment availability, and costs. It is important to consider all these factors during the product design stage, so that the parts and tooling can be designed to meet the assembly needs.

Calibre polycarbonate is an ideal material for various welding techniques because of its amorphous structure. That structure results in a material that is rigid, and has a broad softening temperature range. Also, because it is noncrystallizing, polycarbonate is welded without acquiring thermal stresses. These properties qualify Calibre resins for both vibrational (frictional) and direct-heat welding.

Table 27.1. Overall Comparison of Joining Methods for Tuffak Polycarbonate Sheet

Method of Joining	**Solvent Cement**	**Adhesive Bonding**	**Self-tapping Screws**	**Medium Screws**	**Rivets**	**Hot Gas Welding**	**Hot Blade/ Plate Welding**	**Ultrasonic Welding**	**Vibration Welding**	**Spin Welding**	**Ratings Legends**	
											10=	**1=**
Tensile strength	8	4	10	10	10	10	10	10	10	10	Parent material strength	Poor
Speed	3	2	2	1	3	2	7	10	6	6	Fast	Slow
Tooling	–	1	1	1	3	5	7	8	8	5	Costly	Inexpensive
Labor	1	2	2	1	3	2	9	10	9	10	High	Low
Capital investment	1	1	2	2	2	4	6	9	8	5	Highest	Lowest
Cosmetic appearance	10	3	5	5	5	2	8	9	9	8	Best	Worst
Setup preparation	1	2	3	3	3	6	8	8	7	5	Long	Short
Part size	10	10	10	10	10	8	6	2	4	6	Unlimited	Small
Dissimilar materials	Yes	Yes	Yes	Yes	Yes	?	No	No	Ok	No		
Part design	9	10	10	10	10	5	6	1	8	3	Simple	Limited complex
Cost of materials	9	6	4	1	3	10	10	10	10	10	Most expensive	Least expensive

Reference: *Calibre Engineering Thermoplastics Basic Design Manual*, Supplier design guide (301-1040-1288), Dow Chemical Company, 1988.

27.2 Heated Tool Welding

Bayer: Apec, Makrolon

The recommended hot plate welding parameters for Apec polycarbonate are:

- Hot plate temperature: 280–410°C (536–770°F)
- Joining pressure: 0.1–0.9 N/mm^2 (14.5–130 psi)

The recommended hot plate welding parameters for Makrolon polycarbonate are:

- Hot plate temperature: 250–410°C (482–770°F)
- Joining pressure: 0.1–0.9 N/mm^2 (14.5–130 psi)

Reference: *Hot Plate Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

GE Plastics: Lexan 141

The thickness of the HAZ was approximately 2.5 mm (1 inch) for hot plate welds made using the following welding parameters:

- Hot plate temperature: 516 K (469°F)
- Matching time: 10 seconds
- Matching pressure: 659.3 kPa (95.6 psi)
- Heating time: 35 seconds
- Change-over time: 1.5 seconds
- Forging time: 60 seconds
- Forging pressure: 741.7 kPa (107.6 psi)

Reference: Krishnan C, Toussant D, Benatar A: Comparison of weld morphology of polycarbonate and polypropylene for hot plate, vibration and ultrasonic welding. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

Bayer: Makrolon

For polycarbonate sheet sealing, the surface temperature of the blade should be about 550–650°F (290–345°C). You need to regulate the speed of the heated element so that the surfaces to be joined reach a temperature of about 450°F (230°C). Then they are immediately pressed together at a contact pressure of about 100 psi (690 kPa) and held together for a few seconds until the bond solidifies.

Reference: *Engineering Polymers. Joining Techniques. A Design Guide*, Supplier design guide (5241 (7.5M) 3/01), Bayer Corporation, 2001.

Polycarbonate (form: 3 mm (0.118 inch) thick sheet)

With increasing melt layer thickness, hence an increasing hot plate temperature and/or heating time, there was an increase in the component's susceptibility to stress cracking. As far as process control is concerned, this means the lowest possible heating times and hot plate temperatures should be selected. This is not, however, in the interests of the cost efficiency of the process, and the additional costs incurred through increased cycle time must be set against the costs of heated component storage subsequent to the welding process.

Reference: Potente H, Schnieders J: Influence of process parameters on the phenomenon of stress cracking during hot plate welding. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

GE Plastics: Lexan 9030 (form: extruded sheet)

Test specimens were cut from 3.0, 5.8, and 12.0 mm (0.12, 0.23, and 0.47 inch) thick extruded sheet. Welds were made using melt and weld penetrations of 0.13 and 0.66 mm (0.005 and 0.026 inches), respectively, a hot plate temperature of 245°C (473°F) and a seal time of 10 seconds.

Bubbles could be seen in all the welds, concentrated around the central weld plane. They were elongated by the squeeze flow and tended to be larger near the edges. For each thickness, the weld zone thickness increased with the melt time.

Reference: Stokes VK: Comparison of the morphologies of hot-tool and vibration welds of thermoplastics. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

GE Plastics: Lexan 9030 (form: extruded sheet)

In this study, it was shown that high strengths can be attained in hot tool welds of both undried and dried specimens of polycarbonate. However, the hot tool temperature window for attaining high weld strengths is very wide for dried specimens but quite narrow for the undried specimens. The thickness of the part does have a small effect—with increasing part thickness, the optimum temperature process window appears to shift to higher temperatures. A higher weld penetration appears to result in a higher weld strength. An increase in the heating time appears to reduce the hot tool temperature required for obtaining high weld strengths.

Within the weld parameters studied in the undried material, the highest weld strengths, equal to that of the base material, were obtained at the following conditions:

- For 3 mm (0.12 inch) thick specimens:
  - Hot tool temperature 260–290°C (500–554°F); heating time 10 seconds
  - Hot tool temperature 245–290°C (473–554°F); heating time 15 seconds
  - Hot tool temperature 230–275°C (446–527°F); heating time 20 seconds
- For 5.8 mm (0.23 inch) thick specimens:
  - Hot tool temperature 275–305°C (527–581°F); heating time 10 seconds
  - Hot tool temperature 275–290°C (527–554°F); heating time 15 seconds
  - Hot tool temperature 245°C (473°F); heating time 20 seconds
- For 12 mm (0.47 inch) thick specimens:
  - Hot tool temperature 260–275°C (500–527°F); heating time 10 seconds
  - Hot tool temperature 245–275°C (473–527°F); heating time 15 seconds
  - Hot tool temperature 245–275°C (473–527°F); heating time 20 seconds

Based on repeat tests, consistently high weld strengths were demonstrated in 5.8 mm (0.23 inch) thick specimens at a hot tool temperature of 275°C (527°F) and a heating time of 10 seconds, and a hot tool temperature of 245°C (473°F) and heating times of 15 and 20 seconds.

One interesting result was that very high weld strengths, equal to that of the base material, could be obtained in the presence of bubbles in the weld zone. A small number of large bubbles did not have much effect. However, a large number of small bubbles did result in reduced strength.

While hot tool welding can produce strong welds, it requires careful dimensional and temperature control, and a continuous cleaning of the hot-tool surface.

Reference: Stokes VK: A phenomenological study of the hot-tool welding of thermoplastics. Part 1: polycarbonate. *Polymer*, 40, p. 6235, 1999.

GE Plastics: Lexan 9030 (form: sheet)

High strengths can be attained in hot tool welds between very dissimilar materials. In hot-tool welds of polycarbonate to the semicrystalline polyester PBT, weld strengths equal to that of PBT are obtainable. The use of different hot-tool temperatures is important for obtaining high strengths in welds between dissimilar materials. The hot-tool temperatures varied from 232–316°C (450–600°F) for polycarbonate and from 246–316°C (475–600°F) for PBT. In addition to the hot tool temperatures, the weld strength also depends on the melt time. The highest weld strengths were attained at the longer melt time of 20 seconds. The very high weld strengths obtained for hot tool welding are consistent with those obtained in vibration welds of these two materials.

Although the two imiscible, amorphous polymers polycarbonate and polyetherimide have glass transition temperatures of 150°C (302°F) and 215°C (419°F), respectively, weld strengths comparable to the strength of polycarbonate can be attained. The use of different hot-tool temperatures is important for obtaining high strengths in welds between dissimilar materials. In addition to the hot-tool temperatures, the weld strength also depends on the melt time.

High relative strengths are obtained for heated tool temperatures in the range of 575–625°F (302–329°C) for polycarbonate and 700–750°F (371–399°C) for polyetherimide. Relative strengths (weld strength/strength of polycarbonate) of 0.83 can be attained. This is lower than the 0.95 relative strength obtained in vibration welds. Relative strengths at a polyetherimide heated tool temperature of 800°F (427°C) appear to vary erratically. This could be due to degradation of polyetherimide at this high temperature and deposits on the hot plate surfaces affecting the cleanliness of the molten plastic layers.

Reference: Stokes VK: Experiments on the hot-tool welding of dissimilar thermoplastics. ANTEC 1993, Conference proceedings, Society of Plastics Engineers, New Orleans, May 1993.

Bayer: Makrolon

Makrolon polycarbonate may be heat welded and sealed, following procedures similar to those used for other plastics.

Parts molded of Makrolon polycarbonate resin to be joined by heat welding or sealing must be predried at 250°F (121°C) if maximum bond strengths are to be obtained. Drying times at this temperature are dependent on part thickness.

Reference: *Makrolon Polycarbonate—A Guide for Joining Techniques*, Supplier design guide (55-A664(10)C), Bayer, 1987.

27.3 Ultrasonic Welding

Bayer: Makrolon; Apec

At a frequency of 20 kHz, an amplitude of 25–40 μm (0.0010–0.0016 inches) is recommended for ultrasonic welding of Makrolon and Apec polycarbonate.

Reference: *Ultrasonic Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

GE Plastics: Lexan 141

The size of the HAZ was approximately 200 μm (0.008 inches) for ultrasonic welds made using the following welding parameters:

- Weld time: 0.3 seconds
- Hold time: 2.0 seconds
- Booster: 2:1
- G-pressure: 275.8 kPa (40 psi)

Due to the rapid heating and cooling, very high stresses were developed during ultrasonic welding.

Reference: Krishnan C, Toussant D, Benatar A: Comparison of weld morphology of polycarbonate and polypropylene for hot plate, vibration and ultrasonic welding. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

Bayer: Makrolon DP1-1456 (features: impact-modified, high-flow)

Injection-molded tensile bars with and without a 90° energy director were ultrasonically welded using four different welding modes: time, depth reference point numeric (RPN), energy, and absolute distance. Results showed that impact-modified, high-flow polycarbonate parts can be welded successfully under a variety of welding conditions.

Reference: Chung JYJ: Effects of ultrasonic welding conditions on weld strength of impact-modified, high-flow polycarbonate. ANTEC 1997, Conference proceedings, Society of Plastics Engineers, Toronto, May 1997.

Polycarbonate

This study concluded that amplitude profiling promotes stronger ultrasonic welds in polycarbonate due to reduced residual stresses and increased molecular randomness. Amplitude profiling does not reduce polymer degradation. This was shown by comparing the molecular weights of welded material to those of the as molded material (unwelded sample).

The relationship of weld strength and weld/hold force for the materials was studied. It is seen that weld strength is generally inversely proportional to weld force. High weld force promotes strong molecular alignment and results in weaker welds. At the lower weld forces (<455 N; 102 lbf) this relationship does not hold true due to sample warpage. By varying the force during the weld cycle, it was found that both short cycle times and strong welds could be achieved simultaneously. Force profiling results in maximized weld strengths while the weld time was decreased by 43% for polycarbonate. In polycarbonate, the weld strength did not increase with force profiling since the final weld force is low and allows the polymer chains to solidify in a relaxed state.

When both amplitude and force profiling are used, increased strength and decreased weld time result compared to welds made without any profiling. The increased strength comes from the reduced molecular alignment. The reduced cycle time is a result of using high weld forces to initiate the weld. In summary, a relatively high amplitude and force is used to start the weld quickly and a relatively low amplitude and force is used to complete the weld with minimal molecular alignment.

Reference: Grewell DA: Amplitude and force profiling: studies in ultrasonic welding of thermoplastics. ANTEC 1996, Conference proceedings, Society of Plastics Engineers, Indianapolis, May 1996.

Polycarbonate

Ultrasonic welding is a very complex process that is difficult to control. Two approaches for improving the control of ultrasonic welding were investigated—power threshold control and closed-loop power tracking. Power threshold control relies on the rapid rise in power that is observed near the end of welding for triggering a shutoff of the ultrasonic vibration. For closed-loop power tracking of a preset power curve, the amplitude of vibration is varied in real time in order to impose a power curve that is known experimentally to produce good joints. For polycarbonate, these two approaches were equal to the energy mode and displacement mode in producing strong joints with low standard deviations. The time mode was less effective in producing strong joints for polycarbonate.

The effect of hold pressure on joint strength was also evaluated. As is the case for hot plate welding, decreasing the hold pressure prior to the end of welding improved the joint strength substantially while decreasing the standard deviation. Lower hold pressures result in reduced squeeze out of the molten polymer, thereby permitting more time for intermolecular diffusion.

Also, the lower pressure reduces the molecular orientation that develops parallel to the welds, thereby improving the joint strength.

Reference: He F: Effect of amplitude and pressure control on the strength of ultrasonically welded thermoplastics. ANTEC 1996, Conference proceedings, Society of Plastics Engineers, Indianapolis, May 1996.

Polycarbonate

In this ultrasonic welding study, welding profiles used were a constant amplitude profile, and three amplitude profiles including: an inclining curve, a declining curve, and a pyramid curve. These profiles were used to weld a shear joint in a part made of polycarbonate. The responses that were used to evaluate each curve were flash, tensile strength, and tensile strength standard deviation. Since all of the curves provided tensile results that were both acceptable and comparable, the most important response was determined to be the amount of flash. This was the response that was used as the basis for evaluating how each curve affected the welding of a shear joint.

From the results obtained, the curve which leads to the least amount of flash was the decline curve. It can be theorized that the reason for this was that the high initial amplitude generated enough heat to create a good melt front. Then as amplitude tapered off, there was less energy being put into the part and consequently less flash was squeezed out. Since a good melt front was generated, the parts welded together very nicely. This led to a strong weld which had less flash. This theory can also be seen less dramatically in the results obtained from the pyramid curve. The pyramid curve had the second lowest amount of flash generated. Like the declining curve, the pyramid curve ended with a declining amplitude and, therefore generated less flash. But, since the amplitude was minimal at the beginning of the pyramid curve, there was not as good a melt front created and therefore, the tensile breaking force was a little less than the declining curve, but still relatively strong.

The opposite of this theory can be seen when investigating the results obtained from the inclining curve and the constant amplitude curve. These curves led to significantly higher amounts of flash than the declining or pyramid curves. The constant amplitude curve showed somewhat similar results to the inclining curve: excessive flashing, but the tensile strength was less affected.

From these results, a conclusion on how different amplitude profiles affect an ultrasonically welded shear joint in a part made of polycarbonate can be drawn. It can be concluded that when ultrasonically welding a shear joint made from polycarbonate, a declining amplitude profile will lead to less flash and still provide a strong weld.

Reference: Ford RL, Driscoll SB: Ultrasonic welding with amplitude profiling. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

Polycarbonate

Using parameters indicative to industrial applications results in weld strengths of 2967 N (667 lbf) with a standard deviation of ±1041 N (234 lbf). If the amplitude is varied, weld strengths as high as 7735±138 N (1739±31 lbf) can be achieved, which nearly matched the parent material strength of 7850 N (1765 lbf) (Fig. 27.1). In fact, in these welds, failure usually occurred outside the weld zone when tested in tension.

It has been shown that varying the amplitude during the ultrasonic weld allows better control of the melting process. By reducing the amplitude during the welding cycle it is possible to:

- Maintain the melt within the bond line.
- Obtain stronger welds compared to welds made with a constant amplitude.
- Decrease part marking.
- Increase weld consistency.

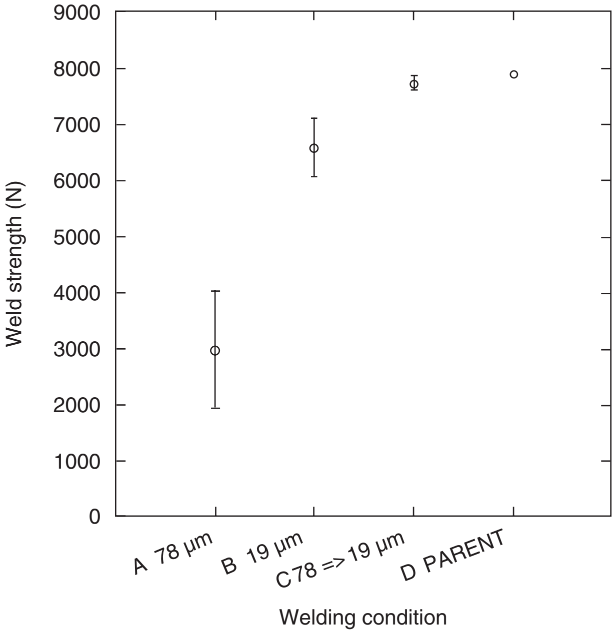


Figure 27.1. Weld strength for polycarbonate test samples ultrasonically welded with various amplitude conditions. Tests with two numbers (i.e., 78 ⇒ 19 μm) represent the use of amplitude profiling.

Ultrasonically Welded Hermetic Seal with No Flash Application Case Study

The application consists of a polycarbonate tube containing a step joint. The requirements were for a hermetic seal with no flash outside the bond line. Using constant amplitude during the welding cycle, resonant modes of vibrations would develop within the parts. These modes of vibrations would result in some areas of the bond line being over-welded with flash extending outside the bond line, while other areas would not be welded. Attempts to modify the tooling to assure a uniform horn amplitude across the entire face of the horn did not improve weld consistency.

However, when the amplitude was modified, more uniform welds were obtained. Using a relatively high amplitude to initiate melting and reducing the amplitude during the cycle reduced the undesirable vibrations and allowed uniform welding. It is important to note the simultaneous change in power and velocity once the amplitude is reduced, which allows the parts to move more uniformly. The only disadvantage is a 40% increase in weld time (from 250 ms to 350 ms).

Reference: Grewell DA, Frantz JL: Amplitude control in ultrasonic welding of thermoplastics. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

Dow Chemical: Calibre 2061-15 (features: medical grade, transparent; melt flow index: 15 g/10 minutes); **Calibre 2080-15** (features: gamma radiation stabilized; note: high acrylonitrile content)

This study was designed to identify which resins could be effectively ultrasonically welded to themselves and other resins, and to identify the maximum bond integrity. Besides looking at the weld strength of various thermoplastic resins, this study explores the effects of gamma radiation and ethylene oxide (EtO) sterilization on the strength of these welds. A wide variety of resins used in the healthcare industry were evaluated, including: ABS, polycarbonate (PC), polycarbonate/ABS blends (PC/ABS), styrene acrylonitrile (SAN), thermoplastic polyurethanes (TPU), rigid TPUs (RTPU), high impact polystyrene (HIPS), and general purpose polystyrene (GPPS).

The strength of customized “I” beam test pieces was tested in the tensile mode to determine the original strength of each resin in the solid, nonbonded test piece configuration. Data from this base-line testing were used to determine the percent of original strength that was maintained after welding. Only amorphous resins were used in this study. The most commonly used energy director for amorphous resins, a 90° butt joint, was used as the welding architecture.

Every attempt was made to make this a “real world” study. The aim during the welding process was to create a strong weld, while maintaining the aesthetics of the part. One of the most important factors in determining whether or not a good weld had been achieved was the amount of flash, or overrun noticed along both sides of the joint. Another characteristic of a good weld was a complete wetting of the cross-sectional weld area. The problem here, however, was that only clear polymers used as the top piece allowed the whole weld to be seen.

Almost all resins involved in the study could be welded together with some degree of success (except for thermoplastic urethanes which did not bond to the polystyrenes). Overall, it appeared that resin compatibility and the ability to transfer vibrational energy through a part, and not similar glass transition temperatures, were the overriding characteristics that lead to the best welds. Although not shown in this study, it should be noted that the ability of a resin to be welded is also a function of the architecture of the ultrasonic weld. Some resins which welded well in the architecture used for this study may not weld well with other architectures.

The PC resins bonded very well with themselves and the ABS resins. Limited success was achieved in bonding PC to the PC/ABS blend and the SAN, however, they bonded poorly or not at all with the urethanes and the polystyrenes. Statistically, the EtO and gamma sterilization did not weaken the bonds for the polymers tested in this short-term study.

Reference: Kingsbury RT: Ultrasonic weldability of a broad range of medical plastics. ANTEC 1991, Conference proceedings, Society of Plastics Engineers, Montreal, May 1991.

Dow Chemical: Calibre (features: transparent)

Calibre polycarbonate is well-suited to ultrasonic welding. The only concerns on the use of ultrasonic welding with these resins are: high energy levels are required to melt the resin; and any contaminants on or in the resins, especially moisture and spray mold release, can result in a poor weld.

Calibre polycarbonate can be ultrasonically welded to itself or to polycarbonate/ABS alloys with excellent results. In some instances, it can be welded to acrylics, to polyphenylene-oxide based resins, and to polysulfones. Calibre polycarbonate is a good ultrasonic welding material, even when the induced vibration must travel through a 0.25 inch (6.4 mm) thick wall to reach the joint site.

An important factor in the ultrasonic welding process is the design of the joint. Decision on the design must include the material, the part geometry, and the requirements of the product. Several standard joint designs are available to meet those needs. Calibre polycarbonate has been successfully welded using the most common "ultrasonic" joint designs, especially when an adequate energy director was used to initiate the melting process.

Reference: *Calibre Engineering Thermoplastics Basic Design Manual*, Supplier design guide (301-1040-1288), Dow Chemical Company, 1988.

Bayer: Makrolon

Makrolon polycarbonate joined by ultrasonic welding can result in excellent, trouble-free bonds if done correctly. Makrolon polycarbonate may also be welded to some grades of ABS and to Bayblend polycarbonate/ABS blend.

In general, fillers such as glass do not inhibit welding. However, when glass content is 10% or higher, horn wear can occur. Poor bonding can result when glass content is 30% or more. Some external mold release agents, lubricants, and flame retardants also can adversely affect the quality of the welds.

The following points should be considered for optimum welding results:

- Be sure the horn, parts, nest, and so forth, are in true alignment to each other.
- When the joint design is a butt joint with an energy director, the energy director should be at least 0.018–0.020 inches (0.46–0.51 mm) high. The apex angle can be 60°–90°.
- A design that employs near-field welding is best.
- If a hermetic seal is required, a shear joint will give the best results.

Reference: *Makrolon Polycarbonate—A Guide for Joining Techniques*, Supplier design guide (55-A664(10)C), Bayer, 1987.

GE Plastics: Lexan

Ultrasonic bonding can be utilized when Lexan resin is to be welded to itself, to some grades of ABS, and to some grades of polycarbonate alloys. The most important element in designing Lexan resin parts for ultrasonic welding is the joint design.

Weldability is dependent upon the concentration of the vibratory energy per unit area. Since Lexan resin has a higher melting point than many other thermoplastics, more energy is required to cause the material at the joint to flow. Therefore, the energy director for welding Lexan resin parts should be fairly tall with a minimum height of approximately 0.2 inches (5.1 mm) and a width of approximately 0.25 inches (6.4 mm).

Parts should be joined immediately after molding. If joined later, predrying may be necessary to provide maximum joint strength. This should be done in a hot air (250°F (121°C)) recirculating oven for one to two hours. Parts should be joined as soon as possible after removal from the oven.

Reference: *Lexan Design Guide*, Supplier design guide (CDC-536E), General Electric Company, 1986.

27.4 Vibration Welding

Bayer: Apec, Makrolon

For linear vibration amplitudes between 0.6 and 0.9 mm (0.024–0.035 inches), and orbital vibration amplitudes between 0.4 and 0.7 mm (0.016–0.028 inches), the recommended welding pressure for Apec and Makrolon polycarbonate is between 1 and 2 N/mm^2 (150–300 psi).

Reference: *Vibration Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

GE Plastics: Lexan 141

The size of the HAZ was approximately 260 μm (0.01 inches) for vibration welds made using the following welding parameters:

- Peak-to-peak amplitude: 0.76 mm (0.03 inches)
- Pressure: 206.84 kPa (30 psi)
- Weld time: 1 second

Much higher residual stresses were developed during vibration welding, compared to hot plate welding.

Reference: Krishnan C, Toussant D, Benatar A: Comparison of weld morphology of polycarbonate and polypropylene for hot plate, vibration and ultrasonic welding. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

GE Plastics: Lexan 141 (form: injection-molded plaque)

This work compares the differences in weld quality between orbital and linear vibration welding of various thermoplastics. The control parameters were varied as follows:

- Amplitude: 0.76–1.8 mm (0.03–0.07 inches) peak-to-peak
- Clamping pressure: 1.0–6.9 MPa (145–1001 psi)
- Collapse: 0.76–1.8 mm (0.03–0.07 inches)

Results showed that there was little difference in the maximum weld strength between linear and orbital welding. Therefore, orbital welding enables a 30% or more reduction in cycle time without loss in maximum weld strength.

The weld strength increased rapidly with collapse and then levelled off once the steady-state phase was reached. Orbital welding required approximately 0.05 mm (0.002 inches) less collapse than linear vibration welding to achieve comparable weld strengths.

Reference: Grewell DA, Benatar A: An application comparison of orbital and linear vibration welding of thermoplastics. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

GE Plastics: Lexan 9030 (form: extruded sheet)

Test specimens were cut from 3.0, 5.8, and 12.0 mm (0.12, 0.23, and 0.47 inch) thick extruded sheet. Welds were made at a frequency of 120 Hz, a weld amplitude of 1.59 mm (0.063 inches), a nominal penetration of 0.5 mm (0.02 inches) and weld pressures between 0.52 and 13.79 MPa (75–2000 psi).

At the lowest weld pressure (0.52 MPa; 75 psi), gas bubbles could be seen in the central weld plane; the density of bubbles increased from the center to the edges. At 0.9 MPa (131 psi), the bubbles were confined to the outer edges of the specimen. At higher pressures, no bubbles could be seen in the weld zone. The thickness of the weld zone decreased with increasing weld pressure.

Reference: Stokes VK: Comparison of the morphologies of hot-tool and vibration welds of thermoplastics. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

GE Plastics: Lexan 9030 (form: extruded sheet)

Under the right conditions, very high weld strengths can be achieved in 120 Hz cross-thickness welds of PC, with weld strengths equal to the base resin. Cross-thickness welds do not necessarily attain the highest strengths at the process conditions under which normal-mode welds have high strengths. Therefore, optimum weld conditions for low frequency (120 Hz) welds must be based on cross-thickness weld data.

At a welding frequency of 120 Hz, the cross-thickness weld strength increases with the weld amplitude and the weld pressure. The strength appears to continue to increase with the penetration up to a threshold penetration, which is higher than the threshold for normal-mode vibration welding of PC. This can be explained by the fact that in cross-thickness welds, steady-state conditions are attained at larger penetrations—of the order of 0.3 mm (0.012 inches)—than for the normal mode welds. Under the right conditions, weld strengths equal to the strength of PC can be achieved. For a weld pressure of 3.45 MPa (500 psi), a penetration of 0.25 mm (0.01 inches) should result in very high strengths.

At the higher frequency of 250 Hz, excellent cross-thickness weld strength can be achieved in PC, and the optimum conditions are the same as for normal-mode welds.

Reference: Stokes VK: Cross-thickness vibration welding of polycarbonate, polyetherimide, poly(butylene terephthalate) and modified polyphenylene oxide. *Polymer Engineering and Science*, 37(4), p. 715, April 1997.

GE Plastics: Polycarbonate

Achievable strengths of vibration welds of polycarbonate to itself and other thermoplastics are given in Table 27.2.

Reference: Stokes VK: Toward a weld-strength data base for vibration welding of thermoplastics. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

GE Plastics: Lexan 9030 (features: 5.8 mm (0.228 inches) thick; form: sheet)

Under the right conditions, the strengths of cross-thickness vibration welds of polycarbonate (PC) can equal the strength of PC. This is achieved for example, for 120 Hz welds at a weld pressure of 3.45 MPa (500 psi), amplitudes greater than 1.27 mm (0.05 inches), and penetrations greater than 0.25 mm (0.01 inches). For an amplitude of 0.95 mm (0.037 inches), all other conditions remaining the same, it may also be possible to achieve very high weld strengths at higher penetrations, but more data are required to confirm this.

Reference: Stokes VK: Cross-thickness vibration welding of thermoplastics. ANTEC 1992, Conference proceedings, Society of Plastics Engineers, Detroit, May 1992.

Table 27.2. Achievable Strengths of Vibration Welds of Polycarbonate to Itself and Other Thermoplastics

Material Family	**PC**							
Tensile strength[b], MPa (ksi)	68 (9.9)							
Elongation @ break[b], %	6							
Specimen thickness, mm (in.)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	3.2 (0.125)	6.3 (0.25)	6.3 (0.25)
Mating Material								
Material family[a]	ABS	M-PPO	M-PPO/ PA	PC	PBT	PC/ABS	PC/ PBT	PEI
Tensile strength[b], MPa (ksi)	44 (6.4)	45.5 (6.6)	58 (8.5)	68 (9.9)	65 (9.5)	60 (8.7)	50 (7.3)	119 (17.3)
Elongation @ break[b], %	2.2	2.5	>18	6	3.5	4.5		6
Specimen thickness, mm (in.)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	3.2 (0.125)	6.3 (0.25)	6.3 (0.25)
Process Parameters								
Process type	Vibration welding							
Weld frequency	120 Hz							
Welded Joint Properties								
Weld factor (weld strength/weaker virgin material strength)	0.83	0.24	0.29	1.0	1.0	0.7	1.0	0.95
Elongation @ Break[b], % (nominal)	1.7	0.4	0.75	6	1.7	1.8	4.9	2.75

[a] ABS:acrylonitrile-butadiene-stryrene copolymer; M-PPO: modified polyphenylene oxide; M-PPO/PA: modified polyphenylene oxide/polyamide alloy; PC: polycarbonate; PBT: polybutylene terephthalate polyester; PC/ABS: polycarbonate/ABS alloy; PC/PBT: polycarbonate/PBT alloy; PEI: polyetherimide.

[b] Strain rate of 10^{-2} s^{-1}.

GE Plastics: Lexan 9030 (form: sheet)

In the vibration welding of polycarbonate, the overall cycle time will increase with increasing part thickness for fixed weld parameters (frequency, amplitude, and pressure), due to an increase in the times spanned by Phases II–IV of the welding process. The penetration at which steady-state conditions are attained (and hence the threshold penetration) increases with specimen thickness, but decreases with increasing weld pressure. Therefore, cycle times can be reduced by increasing the weld pressure.

Low weld pressures not only result in increased cycle times, but can result in unacceptably high threshold penetrations. For example, while a pressure of 0.9 MPa (130 psi) results in acceptable cycle times and threshold penetrations for part thicknesses below 5.8 mm (0.228 inches), higher pressures are indicated for thicknesses equal to 12.3 mm (0.484 inches). If penetration-based controls are used for terminating the weld cycle, then the threshold penetration must be adjusted to account for both the pressure and part thickness.

Reference: Stokes VK: Thickness effects in the vibration welding of polycarbonate. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

GE Plastics: Lexan 9030 (features: 5.8 mm (0.228 inches) thick; manufacturing method: extrusion; form: sheet)

This study showed that under the right conditions, very high strengths and ductilities can be achieved in polycarbonate to polyetherimide vibration welded joints. These joints can attain the strength of PC, the weaker of the two materials.

However, the conditions for achieving high strengths are different from those for neat resins, and cannot be determined from penetration-time curves alone. In neat resins, high strengths are achieved once the penetration rate reaches a steady state, so that penetration-time curves can be used for determining optimum welding conditions. On the other hand, because of differences in “melt” temperatures and viscosities, the apparent steady-state conditions indicated by penetration-time curves for PC to PEI welds are deceptive. The process is dominated by the high melting and flow rates of PC, which masks the still developing melt and flow conditions in PEI when an apparent steady state has been attained. As a result, weld strength continues to increase with penetration, even when this penetration falls in the steady-state regime. Because of this, additional information is required for optimizing PC to PEI welds.

Scanning electron microscopy studies have demonstrated that the dominant mechanism for bond strength during the early stages of welding is the mechanical interlocking at the weld interface produced by shear mixing of the two molten polymers. Process conditions affect the thickness and structure of the zone over which this mixing and interlocking occurs.

The fracture surfaces of PC to PEI welds are interesting. The high-strength welds have deep ridges on both halves of the fracture interface. The depth of the ridges, and the strength appear to increase with the weld pressure. There is a major difference between low-frequency and high-frequency welds. At 120 Hz, the ridges are perpendicular to the direction of the vibratory motion. Although nominally parallel, these ridges exhibit a "wavy" structure. On the other hand, at frequencies equal to 250 and 400 Hz, the ridges are parallel to the direction of motion. Also, the ridge structure is more parallel, and better defined. These well-defined ridges, which appear in the high-frequency (low-amplitude) welds are probably caused by flow instabilities.

Reference: Stokes VK, Hobbs SY: Strength and bonding mechanisms in vibration-welded polycarbonate to polyetherimide joints. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

Bayer: Makrolon

Frictional heat is generated by pressing the surfaces of two parts made from Makrolon polycarbonate together at a pressure of 200–245 psi (1.4–1.7 MPa) and vibrating one against the other through a small displacement. When a molten state is reached at the joint interface, the vibrating action stops, parts are aligned, and a clamp pressure is briefly applied. Overall cycle times can be 4–15 seconds.

Reference: *Makrolon Polycarbonate—A Guide for Joining Techniques*, Supplier design guide (55-A664(10)C), Bayer, 1987.

Polycarbonate

Aircraft air diffuser ducts made from polycarbonate were first assembled with epoxy, requiring sandblast preparation and prebonding of parts. Also required were expensive fixturing devices with clamp arrangements and a 24-hour cure time.

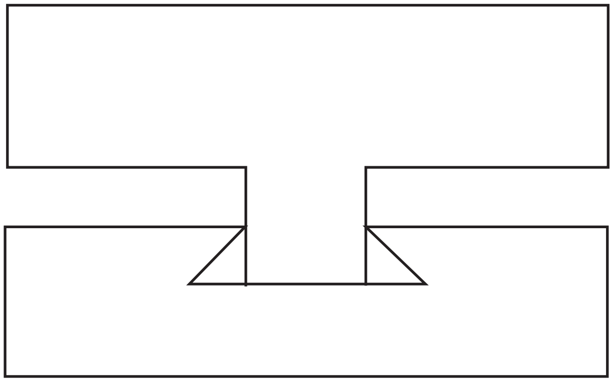
Vibration welded production is up from less than one part per minute to three parts per minute. Labor cost was cut by 70%, and the total part cost was cut considerably.

Reference: White P: Vibration welding. *Making It With Plastics*, Trade Journal, 1987.

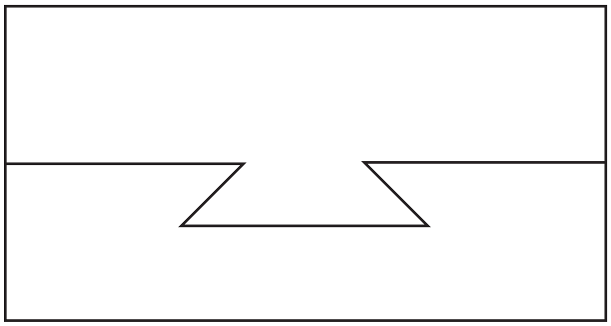
GE Plastics: Lexan

Dissimilar materials may be joined to Lexan resin by vibration welding, and a special dovetail/tongue-in-groove joint design (Fig. 27.2). Using this method, a mechanical bond is formed by melting the material with the lower melt viscosity into the material with the higher melt viscosity.

Reference: *Lexan Design Guide*, Supplier design guide (CDC-536E), General Electric Company, 1986.



Before exposure



After exposure

Figure 27.2. Joint design for vibration welding dissimilar materials to GE Plastics Lexan polycarbonate.

27.5 Spin Welding

Dow Chemical: Calibre (features: transparent)

Calibre polycarbonate is well-suited to spin welding.

Three variables affect the spin weld process: speed of rotation, duration of rotation, and pressure applied to the joint. Each of the variables depends on the material and the diameter of the joint. In most cases, the actual spin time should be approximately 0.5 seconds, with an overall weld time of 2.0 seconds. When assembly by spin welding is proposed, a prototype evaluation should be done to determine the rotation speed and time, pressure, and holding time that fit the application.

Reference: *Calibre Engineering Thermoplastics Basic Design Manual*, Supplier design guide (301-1040-1288), Dow Chemical Company, 1988.

Bayer: Makrolon

With one part held stationary, the other is rotated at 300–500 rpm with enough pressure applied to keep the parts in contact with each other. The heat generated by the friction is used to bring the surfaces to a sealing temperature of about 425°F (218°C). When sufficient melt is obtained, the spinning stops and the pressure is increased to distribute the melt and also to squeeze out excessive melt, completing the bonding process.

In some cases, the stationary part can be made to rotate with the moving part when the driver stage of spinning is disengaged. This is to counteract the inertial forces incurred in stopping the rotating part.

Reference: *Makrolon Polycarbonate—A Guide for Joining Techniques*, Supplier design guide (55-A664(10)C), Bayer, 1987.

27.6 Radio Frequency Welding

Polycarbonate

The glass transition temperature of polycarbonate is significantly higher than that of the other materials in this radio frequency welding study. Because of this, considerable difficulty was experienced in sample preparation. In the light of this, it was considered unlikely that sound bonds could be achieved between polycarbonate and other materials studied (flexible PVC, rigid PVC, polyurethane, styrenic TPE). There is not sufficient overlap in the temperature ranges in which these materials soften.

Reference: Leighton J, Brantley T, Szabo E: RF welding of PVC and other thermoplastic compounds. ANTEC 1992, Conference proceedings, Society of Plastics Engineers, Detroit, May 1992.

27.7 Laser Welding

Sheffield Plastics: Hyzod GP (form: sheet)

The objective of this study was to determine the effect of welding parameters (power, focal spot size, and travel speed) on weld size and weld quality in terms of hermetic seal and strength. Two focal spot sizes were used (25 and 50 μm; 0.001 and 0.002 inches). A transparent bladder was used to applied weld pressure. The pressure in the bladder was varied from 0.02 to 0.45 MPa (3–65 psi).

The results showed that, in general, the weld strength was proportional to the weld width (which was between 50 and 300 μm; 0.002 and 0.012 inches), and that maximum weld strength was seen with a heat input of 0.025 J/mm. It was also seen that the weld strength is relatively independent of bladder pressure. It is believed that this is due to the fact that the true pressure developed within the weld is a function of thermal expansion of the material.

Reference: Grewell D, Benatar A: Experiments in microwelding of polycarbonate with laser diodes. ANTEC 2003, Conference proceedings, Society of Plastics Engineers, Nashville, May 2003.

PC

Transmittance and reflectance of PC were measured for various thicknesses and incident angles of the laser beam (from a 50 W diode laser with a wavelength of 810 ±10 nm). The optical properties of PC did not depend on the thickness. Transmittance of PC was high, making it well-suited for through transmission laser welding (TTLW). Reflectance increased and transmittance decreased with increasing incident angle. However, even for an incidence angle of 75° the transmittance was still at 40%, making it acceptable for TTLW.

Reference: Rhew M, Mokhtarzadeh A, Benatar A: Diode laser characterization and measurement of optical properties of polycarbonate and high-density polyethylene. ANTEC 2003, Conference proceedings, Society of Plastics Engineers, Nashville, May 2003.

PC (form: injection-molded AWS G1 ultrasonic weld test sample)

The AWS standard G1 samples were cut to reduce the length from 50.8 mm (2 inches) to 10 or

20 mm (0.39 or 0.79 inches) because of the laser equipment limitations. PC with 0.5% carbon black was used for the absorbent part. Since PC is hydroscopic, all samples were dried prior to welding in a vacuum oven at 121°C (250°F) for 6 hours.

A maximum weld factor of 95% was obtained for a welding power of 4.06 W at the weld interface, a heating time of 20 seconds, and welding pressure of 0.427 MPa (62 psi).

Reference: Rhew M, Mokhtarzadeh A, Benatar A: Through transmission laser welding of polycarbonate and high-density polyethylene. ANTEC 2003, Conference proceedings, Society of Plastics Engineers, Nashville, May 2003.

PC (form: 2.9 mm (0.114 inch) thick injection-molded plaque)

In these experiments, welds were made between 3.2 mm (0.126 inches) thick clear PC (top) and 6.4 mm (0.252 inches) thick black PC (bottom) using a diode laser with an 828 nm wavelength. The pressure was set to 69 kPa (10 psi). The power was varied from 50 to 1000 mW, the travel speed was varied between 30 and 140 mm/s (1.2–5.5 inches/s) and the focal spot size was varied between 25 and 50 μm (0.001–0.002 inches).

Results showed that the weld width was directly proportional to power level.

Reference: Grewell D, Jerew T, Benatar A: Diode laser microwelding of polycarbonate and polystyrene. ANTEC 2002, Conference proceedings, Society of Plastics Engineers, San Francisco, May 2002.

PC (form: 2.9 mm (0.114 inch) thick injection-molded plaque)

Quasi-simultaneous welding involves a laser beam being guided over the length of the weld by means of a mirror system and scanning the joining surface several times over a relatively high speed (up to 10 m/s; 33 ft/s). This ensures a (quasi-) simultaneous and homogeneous heating and plasticization of the adherent surface, and makes it possible to press warped parts to be welded together during welding.

The joining surface was 69 × 2.9 mm (2.72 × 0.114 inches). The applied carbon black content for the absorbing part was 0.1 wt.%. The laser employed was a solid-state (Nd:YAG) laser with a wavelength of 1064 nm. The maximum power output of the laser in continuous-wave operation was approximately 250 W.

For the T-joint geometry, the highest weld strength was 23 N/mm^2 (3300 psi) and was predicted for an intensity of 35 W/cm^2 (4600 psi) and a joining displacement of 1.00 mm (0.039 inches). For the butt joint geometry, the maximum weld strength was established at 32 N/mm^2 (4600 psi) for an intensity of 30 W/cm^2 and a melting displacement of 1.00 mm (0.039 inches).

Reference: Potente H, Fiegler G, Becker F, Korte J: Comparative investigations on quasi-simultaneous welding on the basis of the materials PEEK and PC. ANTEC 2002, Conference proceedings, Society of Plastics Engineers, San Francisco, May 2002.

Polycarbonate (form: sheet)

Experiments showed that PC can be laser-welded with a 150 W diode laser, operating at a wavelength of 808 nm. 8.5 W of laser power was sufficient to weld PC to carbon black pigmented PC at welding speeds of 50 mm/s (2 inches/s), resulting in 1.2 mm (0.047 inch) wide welds. These welds were strong and flexible. Tensile tests showed that a yield strength close to the parent material can be achieved.

PC was also welded with a smaller beam cross-section to produce 0.4 mm (0.016 inch) wide welds at powers <8 W.

Reference: Nilsson T, Lampa C: Diode laser welding of plastics. 7th NOLAMP Conference proceedings, Lappeenranta, Finland, August 1999.

27.8 Induction Welding

GE Plastics: Lexan 9030 (features: extruded sheet)

A commercial high-frequency generator (Emabond Systems HD500) was used for making all the induction welds. Pressure applied by an air cylinder was used to control the weld interface pressure; two weld pressures of 0.21 MPa (30 psi) and 0.41 MPa (60 psi) were used.

Relative weld strengths as high as 48% were demonstrated, although it should be remembered that, while this study focused on the tensile strengths of welds, in induction welding, the weld joints are mainly subjected to shear stresses.

Reference: Stokes VK: Experiments on the induction welding of thermoplastics. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

Dow Chemical: Calibre (features: transparent)

Calibre polycarbonate is suitable for induction welding. It can be welded to itself, to polycarbonate/ABS alloy, acrylics, and to polysulfones. A tongue-and-groove joint design that incorporates a shear-type weld is recommended. This type of joint produces a fast, strong bond.

Reference: *Calibre Engineering Thermoplastics Basic Design Manual*, Supplier design guide (301-1040-1288), Dow Chemical Company, 1988.

Bayer: Makrolon

Makrolon polycarbonate can be electromagnetically welded into strong, clean, structural, hermetic, or high-pressure seals utilizing this process. Besides bonding to itself, Makrolon polycarbonate can be bonded to some grades of ABS, acrylic, polysulfone, and SAN.

Reference: *Makrolon Polycarbonate—A Guide for Joining Techniques*, Supplier design guide (55-A664(10)C), Bayer, 1987.

27.9 Heat Sealing

GE Plastics: Lexan

This work describes experiments in impulse welding of thin polycarbonate films on a carbon-filled polycarbonate substrate, similar to the sealing of micro-channels on a microfluidic device. Pressure burst testing was carried out in order to measure the weld strength. The effects of power and heating time on weld width and weld strength were studied. The weld width was found to increase with power and welding time. Weld strength was found to increase with power and time, until a point beyond which the strength dropped due to possible degradation.

Kapton films were placed on either side of the nichrome wire to avoid sticking. Nichrome wires with diameters of 203.3, 101.6, 50.8 and 35.56 μm (0.008, 0.004, 0.002 and 0.0014 inches) were used. A clamping force of 0.29–0.32 MPa (42–46 psi) was used.

The strongest weld that was produced was 150 μm (0.006 inches) wide with an average weld strength of 26.73 MPa (3877 psi), corresponding to a burst pressure of 0.27 MPa (39 psi). Welds that were as small as 80 μm (0.003 inches) could be made with this process but the strengths were extremely low (<1 MPa; 145 psi).

Reference: Krishnan C, Benatar A: Experiments in impulse welding a thin film lid for sealing micro-channels in microfluidic applications. ANTEC 2005, Conference proceedings, Society of Plastics Engineers, Boston, May 2005.

Bayer: Makrolon

Makrolon polycarbonate films up to 0.25 mm (0.010 inches) thick can be bar sealed. Do not seal thicker sheets in this manner, because bond dimensions may distort. For bar sealing polycarbonate film, the surface temperature of the heater elements should be between 450 and 500°F (230–260°C). Typically, you will need a contact pressure of approximately 100 psi (690 kPa), which usually results in a cycle time of 0.5–2 seconds, depending upon the thickness of the film to be sealed.

Reference: *Engineering Polymers. Joining Techniques. A Design Guide*, Supplier design guide (5241 (7.5M) 3/01), Bayer Corporation, 2001.

27.10 Solvent Welding

Bayer: Makrolon

You can bond parts made of Makrolon polycarbonate using methylene chloride or ethylene dichloride. Methylene chloride's fast evaporation rate helps to prevent solvent–vapor entrapment for simple assemblies. For complex assemblies that require more curing time, use ethylene dichloride because it has a slower evaporation rate, allowing for longer assembly times. Mixing methylene chloride and ethylene dichloride in a 60:40 solution, a commonly used mixture, will give you a longer time to assemble parts than pure methylene chloride because of the reduced evaporation rate.

When using solvent welding techniques with polycarbonate, some embrittlement may occur. The parts can lose some of their excellent impact strength at the weld joint.

A 5–10% solution of polycarbonate in methylene chloride helps to produce a smooth, filled joint, when the mating parts made of Makrolon resin do not fit perfectly. Do not use this mixture to compensate for severely mismatched joints. Increasing the concentration can result in bubbles at the joint.

Tests carried out indicate that methylene chloride-bonded parts had 80–90% of the ultimate bond strength after curing for 1 to 2 days. When working with polycarbonate resins, curing parts for elevated-service use and maximum bond strength is much more complicated. You may have to use a complicated treatment schedule of gradually increasing temperatures for these applications (see Table 27.3).

Reference: *Engineering Polymers. Joining Techniques. A Design Guide*, Supplier design guide (5241 (7.5M) 3/01), Bayer Corporation, 2001.

Table 27.3. Solvent Bond Curing Schedule for Makrolon Resins

Sequential Holding Time, hrs	Part or Bond Temperature, °C (°F)
8	23 (73)
12	40 (100)
12	65 (150)
12	93 (200)
12	110 (225)

Altuglas International: Tuffak (form: sheet)

Solvent welding is the simplest method of joining Tuffak sheet to itself. The solvent type can be (a) pure solvent, (b) a polymerizable monomer/solvent or (c) a thickened solvent. Welded joints have low impact and are not recommended if high impact resistance is necessary.

Pure solvents are water-thin. The most common methods for application of pure solvents are by needle applicator capillary action and edge dipping.

Polymerizable monomer cements will give a better-looking joint than the pure solvent, since voids can be eliminated. However, these joints are more brittle, and they will blush more than a pure solvent joint.

Thickened cements, with 10–15% of the parent material dissolved in a solvent, can be used when mating joint parts that do not fit together. The strength is not as high as a solvent joint.

A good solvent joint should have a tensile strength of 2500 psi (17 MPa). The clearest joint is obtained by putting pressure on the joint using a press while the solvent is drying.

Reference: *Tuffak Polycarbonate Sheet. Forming and Fabrication*, Supplier design guide (ADV980496/APL:ATG-16S/web/6-00), Altuglas International, 2000.

GE Plastics: Lexan 9034 (form: 5.5 mm (0.22 inch) thick sheet)

The relationship of joint strength of solvent-welded joints of polycarbonate to their microstructure was investigated. Three solvents were used: butanone, acetone, and cyclohexanone, together with mixtures of cyclohexanone with ethanol. The effect of welding temperature was also investigated.

Results showed that butanone gave the highest joint strengths, followed by acetone and cyclohexanone. When the concentration of cyclohexanone in ethanol was less than 60 vol%, no welding was observed; polycarbonate treated with cyclohexanone at 78 vol% had the maximum joint strength. Also, the joint strength of polycarbonate treated with cyclohexanone increased with the welding temperature.

Reference: Chang KC, Sanboh L: Strength and microstructure of solvent welded joints of polycarbonate. *Journal of Adhesion*, 56, p. 135, 1996.

Cyro: Cyrolon AR (features: transparent, abrasion resistant coating, 3.2 mm (0.126 inches) thick; manufacturing method: continuous cast; form: sheet)

Cyrolon AR polycarbonate sheets are available with either one or two sides coated from protection against abrasion. When cementing to a noncoated sheet surface, use the same solvent or polymerizing cements commonly used for Cyrolon sheet products. The most critical factor is the edge of the part to be cemented. The edge must first be properly prepared with low stresses. Scraping, wet sanding, and buffing are acceptable methods to prepare a finished edge. Flame polishing is not recommended. Overspray from the flame may cause the surface coating to crack or craze. This may lead to delamination of the coating and a loss of abrasion resistance. Annealing of the part prior to cementing is recommended.

Solvent cementing to a hard-coated surface cannot be readily accomplished due to the chemical resistance of the coating. To solvent cement on or to a coated surface, the coating first must be removed by sanding or routing. When removing the coating, insure that the bonding surface is flat, clean, and free of stress. Annealing the piece will insure a stress-free surface.

Reference: *Physical Properties Acrylite AR Acrylic Sheet and Cyrolon AR Polycarbonate Sheet*, Supplier design guide (1632B-0193-10BP), Cyro Industries, 1993.

Dow Chemical: Calibre 2060-15 (features: transparent); **Calibre Megarad 2080-15** (features: transparent)

In tests conducted to evaluate the bondability/compatibility of plasticized PVC tubing to rigid, transparent thermoplastics, this study presents results for two types of polycarbonate: a general purpose grade and a radiation-stabilized grade. The latter is not to be confused with polycarbonate that has been merely color-compensated to adjust for the characteristic color shift upon exposure to gamma radiation. The distinction refers instead to a specific additive package, which reduces the color shift. Any differences in the bond strength performance and overall bond integrity may be explained by the plasticization effect of the additive, resulting in luers with lower molded-in stress and slight differences in the surface properties.

Straight methylene chloride and acetone were the only solvents which brought about short-term signs of crazing or other solvent attack in the polycarbonate. Cocktails made of 50:50 blends of methylene chloride in cyclohexanone or MEK in cyclohexanone displayed satisfactory bond strengths. Bonds made with THF, cyclohexanone, MEK, or an 80:20 blend of MEK in cyclohexanone were all bordering between marginal and satisfactory ratings based on bond strength. The 1,2-dichloroethane resulted in high bond strengths, though the ease of insertion was marginal for the radiation stabilized version. Insertion was also marginal or unsatisfactory for blends rich in methylene chloride and for acetone. In fact, tubing could not be completely inserted into the radiation stabilized luers using acetone as a solvent, so no accurate tests could be performed. The 50:50 blend of MEK in cyclohexanone is suggested for polycarbonate as the best solvent without any short-term, adverse effects.

Reference: Haskell A: Bondability/compatibility of plasticized PVC to rigid, transparent thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

Dow Chemical: Calibre (features: transparent)

Calibre polycarbonate is well-suited to solvent bonding because of its amorphous nature. The most common solvent used is methylene chloride at varying concentrations. The main limitation of this technique is in the handling of the solvent.

In solvent welding, methylene chloride (or a combination of methylene chloride and ethylene dichloride) is applied to the joint area of one or both components, and the two components are then held together in a fixture. While the parts are held together, and after being subjected to a pressure of 250–500 psi (2–3 MPa), the bond cures to form a joint in 1–5 minutes, depending on the size and shape of the joint area.

Environmental conditions, such as elevated temperatures can cause stress crazing. Therefore, the bond should be dried for 24–48 hours at a temperature just below the maximum anticipated operating temperature. This often eliminates crazing, which can be caused by entrapped solvent.

Reference: *Calibre Engineering Thermoplastics Basic Design Manual*, Supplier design guide (301-1040-1288), Dow Chemical Company, 1988.

Bayer: Makrolon

Solvent welding is a practical method of joining Makrolon polycarbonate to itself or to another plastic soluble in the same solvent. It involves treating the weld area with a minimum amount of solvent to soften the surfaces, then clamping the parts together until the weld takes place.

Welding Procedure: The most common mistake made in making solvent welds is the use of too much solvent. Only the minimum amount required to wet the surface area should be used. Excessive solvent can result in bubbling and squeeze-out, which decreases the strength of the bond.

Before applying solvents, the mating surfaces should be cleaned of any grease, dirt, or foreign matter. Well-mated parts are essential for optimum welds. They should mate with no strain, so that contact pressure may be uniformly distributed over the entire weld area.

In solvent welding, it is best to apply a thin film of the solvent in a quick and efficient manner. With Makrolon polycarbonate, only one of the mating surfaces should be treated with the solvent, and the parts should be clamped together in a pressure fixture within a few seconds. Pressures between 100 and 500 psi (0.7 and 3.4 MPa) should be used for best results.

The ultimate weld strength is primarily a function of solvent concentration on mated surfaces. Therefore, the elapsed time between solvent application and clamping must be carefully controlled because, if too much evaporation occurs, a poor weld will result. The amount of clamp time is not as important, but a minimum of 60 seconds is recommended.

Curing Solvent-welded Parts: Parts solvent welded with methylene chloride which are intended to function at room temperature should be cured for 24–48 hours at room temperature. Adequate air circulation should be provided for efficient solvent vapor removal. Air-tight enclosures where solvent vapors may be trapped should be avoided, since the solvent vapors not removed can lead to embrittlement of the material. Using ethylene dichloride, laboratory tests conducted by Mobay indicated 80–90% of the ultimate weld strength was reached within 1–2 days.

Smaller weld areas might be successfully cured in shorter times, while large areas might require still longer times or narrower temperature intervals to avoid the tell-tale appearance of bubbles in the weld. Uncured parts that are suddenly exposed to service at elevated temperatures may suffer complete joint failure. If exposed to service in hot water, a cloudy, weak weld will result. In general, the highest cure temperature should be equal to, or slightly higher than the highest expected service temperature.

Reference: *Makrolon Polycarbonate—A Guide for Joining Techniques*, Supplier design guide (55-A664(10)C), Bayer, 1987.

GE Plastics: Lexan

Solvent welding is one of several alternatives for joining Lexan resin parts. The joint area for Lexan resin parts that are to be welded with this technique should be designed such that the two parts fit precisely, without pressure, when they leave the mold. Locating pins or tongue-and-groove shapes may be used to align the bonding area and promote rapid part matching after the application of solvent. These devices should be kept shallow to avoid solvent entrapment in the mating surface. Parts to be welded must be molded well, dimensionally, and possess low residual stresses.

The following solvent systems are recommended for parts molded of Lexan resin:

- Methylene chloride, which has a low boiling point of 40.1°C (104.2°F)and an extremely fast evaporation rate.
- A 1–5% solution of Lexan resin in methylene chloride can be used in extreme cases to obtain smooth, completely filled joints when perfectly mated bonding areas are impossible to obtain. This solution has the advantage of a decreased evaporation rate. Higher concentrations of this solution are not recommended because of the great difficulty in obtaining completely bubble-free joints.

When solvent welding parts molded of Lexan resin, use the minimum amount of solvent necessary for good adhesion. This is the opposite of the procedure recommended for other thermoplastics, where one or both halves are soaked in solvent for a considerable period of time. Solvent should be applied to only one of the Lexan resin joint surfaces. The other half should remain dry and ready in the clamping fixture. Surfaces to be welded should be free of dirt, grease, and mold release.

The following two methods of applying methylene chloride enable the minimum amount of solvent to be used to weld Lexan resin parts:

(1) Saturate a piece of felt, sponge, or other absorbent material with solvent. The Lexan resin part to receive the methylene chloride should then be stamped onto the solvent-saturated material and clamped to the mating part with an even pressure distribution (Fig. 27.3).

(2) Make fitting counterparts from wood or metal. Dip the counterparts into the solvent and press against the Lexan resin part surfaces, applying a thin film of solvent. Allow a few seconds for drying and then assemble the parts for welding, applying pressure evenly in a jig or fixture (Fig. 27.4).

Pressure should be applied as soon as the two parts have been put together. Pressure between 200 and 600 psi (1.4–4.1 MPa) is suggested for best results. Holding time in the fixture should be approximately one to five minutes, depending on the size of the bonding area.

The welded joint should be clear and bubble-free. The presence of bubbles indicates either excess solvent and/or insufficient pressure, or too short a pressure hold. Squeeze-out is a sign of excessive pressure. Crystallizing at the weld area indicates excessive solvent

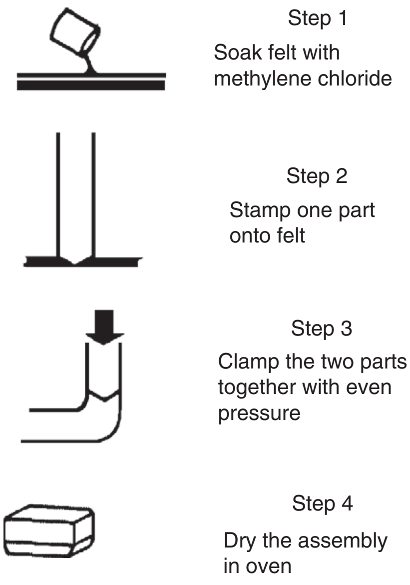


Figure 27.3. Solvent welding Procedure 1 for Lexan polycarbonate.

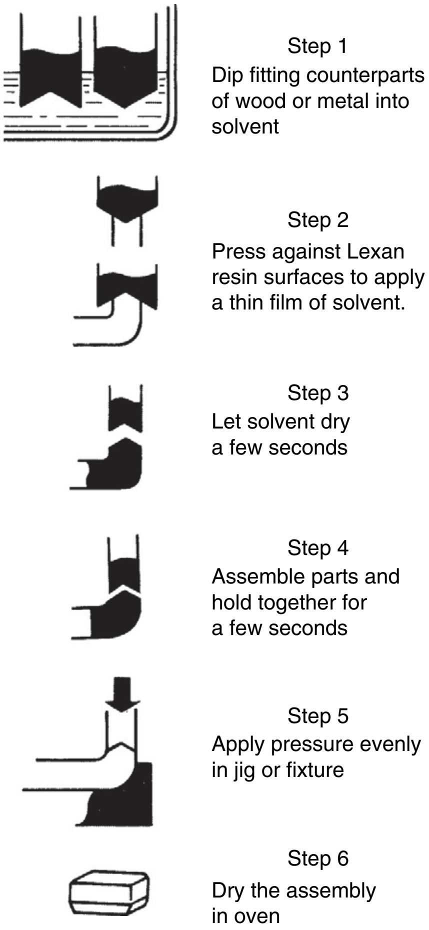


Figure 27.4. Solvent welding Procedure 2 for Lexan polycarbonate.

and too much elapsed time between solvent application and mating of the parts in the pressure fixture.

Although the welded parts may be handled without damage after the holding time in the pressure fixture, sufficient weld strength for room temperature use is normally achieved by drying the welded parts for 24–48 hours at room temperature. If the solvent-welded part is to be used at high temperatures, a longer solvent removal program is necessary. Otherwise, bubbles and a weakened weld result when the temperature is raised. Generally, the solvent removal schedule should ultimately reach a temperature which is equal to or slightly lower than the maximum service temperature. This can be done by raising the temperature 5–10°F (2.8–5.6°C) per hour, depending on the bond size, until the desired temperature is reached.

A typical schedule for a part used at 200°F (93°C) is:

1 hour @ 77°F (25°C)
24 hours @ 100°F (38°C)
24 hours @ 160°F (71°C)
24 hours @ 185°F (85°C)

Reference: *Lexan Design Guide*, Supplier design guide (CDC-536E), General Electric Company, 1986.

GE Plastics: Lexan GR1110 (features: gamma radiation stabilized)

Based on the results of a study to determine the effects of gamma radiation on solvent weld strength, it was found that solvent welding was effective in securing Lexan GR1110 resin. After extremely high dosages of gamma radiation, 10 Mrads, the bond strength was not compromised. In all cases, the mode of failure was within the substrate, indicating that the material broke, not the welded joint. Therefore, the weld strength is greater than, or equal to the values reported.

Methylene chloride/cyclohexanone combination typically yielded the highest results when bonding Lexan resins to PVC.

Reference: *Guide to Engineering Thermoplastics for the Medical Industry*, Supplier design guide (MED-114), General Electric Company.

27.11 Adhesive Bonding

Dow Chemical: Calibre 300-4

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 27.4 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because

Table 27.4. Shear Strengths of Calibre 300-4 PC to PC Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[b]

Material Composition		**Loctite Adhesive**					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	4 rms	750 (5.2)	3850 (26.6)	2000 (13.8)	1600 (11.0)	1100 (7.6)	3700 (25.5)
Roughened	18 rms	1600 (11.0)	4500 (31.0)	3400 (23.5)	3950 (27.2)	1100 (7.6)	4550 (31.4)
Antioxidant	0.1% Irgafos 168 0.1% Irganox 1076	750 (5.2)	3850 (26.6)	2000 (13.8)	3950 (27.2)	550 (3.8)	3700 (25.5)
UV stabilizer	0.4% Tinuvin 234	750 (5.2)	3850 (26.6)	2000 (13.8)	1600 (11.0)	450 (3.1)	3700 (25.5)
Flame retardant	2% BT-93 1% Antimony oxide	1300 (9.0)	>4100[a] (>28.3)[a]	>3800[a] (>26.2)[a]	>3400[a] (>23.5)[a]	300 (2.1)	3700 (25.5)
Impact modifier	5% Paraloid EXL3607	1000 (6.9)	3850 (26.6)	2000 (13.8)	>4500[a] (>31.0)[a]	500 (3.5)	3700 (25.5)
Lubricant	0.3% Mold Wiz INT-33UDK	1300 (9.0)	3850 (26.6)	2000 (13.8)	3850 (26.6)	1100 (7.6)	3700 (25.5)
Glass filler	23% Type 3090 glass fiber	1150 (7.9)	3850 (26.6)	600 (4.1)	2700 (18.8)	1100 (7.6)	4850 (33.5)
Colorant	4% CPC07327	1650 (11.4)	3850 (26.6)	500 (3.5)	3950 (27.2)	1100 (7.6)	3700 (25.5)

[a] The force applied to the test specimens exceeded the strength of the material, resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 27.4, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Flashcure 4305 light cure adhesive achieved bond strengths that were higher than the grade of unfilled polycarbonate tested. Prism 401 and Super Bonder 414, both cyanoacrylate adhesives, Loctite 3105, a light curing acrylic adhesive, and Hysol E30-CL epoxy adhesive, Hysol 3631 hot melt adhesive and Fixmaster high performance epoxy all achieved very high bond strengths on PC. Hysol 3651 and 7804 hot melt adhesives achieved the lowest bond strengths.

Surface Treatments: Surface roughening either caused no effect, or a statistically significant increase in the bondability of PC. The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused a statistically significant decrease in the bond strengths achieved on PC for most of the formulations evaluated.

Other Information: Polycarbonate is generally compatible with acrylic and cyanoacrylate adhesives, but there is a potential for stress cracking. In addition, polycarbonate can be attacked by the activators for two-part no-mix acrylic adhesives before the adhesive has cured. Any excess activator should be removed from the surface of the polycarbonate immediately. Polycarbonate is incompatible with anaerobic adhesives. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

Bayer: Makrolon

UV-cured adhesives, excellent for transparent materials such as Makrolon polycarbonate, cure in seconds and typically have high bond strength. Two-part acrylic adhesives usually show high bond strength. Use care in selecting these adhesives, as some of their accelerators can be very aggressive to Makrolon polycarbonate resins.

Reference: *Engineering Polymers. Joining Techniques. A Design Guide*, Supplier design guide (5241 (7.5M) 3/01), Bayer Corporation, 2001.

Altuglas International: Tuffak (form: sheet)

Adhesive bonding creates the weakest type of joints. It must be used when other methods are not applicable, such as joining two different materials (e.g., Tuffak polycarbonate to metal).

A list of suitable thermosetting adhesive types is given in Table 27.5. Thermoplastic adhesives are not recommended for Tuffak polycarbonates.

Table 27.5. Thermosetting Adhesives Suitable for Bonding Tuffak Polycarbonate

Adhesive Type	Use
Acrylic	When high strength is important, but cosmetic (clarity) is not (brown in color)
Urethane	Useful with jewel trim on sign cans. Is clear, tough, and has good strength; is fast-reacting so special applicator may be necessary
Clear silicone rubber	Useful for sign tie-back; not as strong as urethane, but affects paint less. Used with a primer
Epoxy	Do not use amine-hardened or other rigid systems

Reference: *Tuffak Polycarbonate Sheet. Forming and Fabrication*, Supplier design guide (ADV980496/APL:ATG-16S/web/6-00), Altuglas International, 2000.

Bayer: Makrolon

Makrolon polycarbonate can be bonded to itself and to other substrates with a variety of adhesives including Scotch-Weld 2216 B/A, a two-component epoxy adhesive from 3M Corporation. However, solvent-based adhesives can be harmful to Makrolon polycarbonate if the molded part is subject to stress greater than 1300 psi (9 MPa).

When selecting an adhesive for parts molded of Makrolon polycarbonate resin, consider the following:

- Requirements as to flexibility or rigidity of the assembled parts
- Environmental temperature requirements
- General appearance requirements

An adhesive that can be gravity-fed is easier to handle and to apply. The equipment for dispensing it is also less costly.

When using adhesives, part cleanliness is very important. Make sure that the bonding surfaces are free of all dirt, grease, and other contamination.

Reference: *Makrolon Polycarbonate—A Guide for Joining Techniques*, Supplier design guide (55-A664(10)C), Bayer, 1987.

GE Plastics: Lexan

Parts molded of Lexan resin can be bonded to other plastics, glass, metal, and other materials using a variety of adhesives. Generally, best results are obtained with solventless (100% reactive) materials, such as epoxies, urethanes, and high performance adhesives.

Avoid adhesives containing incompatible constituents or curing agents that are incompatible with Lexan resin. Use curing temperatures below 250°F (121°C) and high (low) temperature adhesives for high (low) temperature applications.

Parts should be thoroughly cleaned before adhesive bonding. All oil, grease, paint, mold releases, rust, and oxides must be removed by washing with compatible solvents such as isopropyl alcohol, petroleum ether, 65°C (149°F) boiling point heptane, VM & P naphtha, white kerosene, or a mild solution of soap. Bond strength may be improved by mild surface abrasion (sanding) as is customary with other materials.

Epoxies: Epoxy adhesives offer an extremely wide range of resistance to moisture, chemicals, and heat. Consulting an appropriate handbook regarding these properties, as well as shear and peel strength, is recommended. Parts molded of Lexan resin can be joined using epoxy systems containing room temperature (RT) curing agents such as diethylene triamine, and polyamides, or with systems containing elevated temperature hardeners such as anhydrides, or Lewis acids. When bonding Lexan resin parts to metal parts, several considerations need to be taken into account. A room temperature cure will reduce the strains created in an adhesive caused by the difference in coefficients of thermal expansion. This thermal expansion difference can cause adhesive cracking and considerably decreases expected bond strength.

However, RT cures tend to form weaker bonds than high temperature cures. To minimize bond strain when using a high temperature adhesive, the grade of Lexan resin and the metal to be joined should be closely matched from a thermal expansion standpoint. Curing temperatures should not exceed 250°F (121°C), the heat distortion temperatures of standard Lexan resin grades. Sulfide modifiers increase elasticity, although at the expense of generally lower bond strength and increased odor. These impact or elastomer modified epoxies permit a fairly thick glue line.

Amine-cured or polyamide-cured epoxies are not generally recommended for hot water or steam environments above 250°F (121°C). Anhydride-cured epoxies usually require a high temperature cure. Before applying epoxy cement, parts should be predried for 2–3 hours at 250°F (121°C) in an air-circulating oven to drive out residual moisture.

RTV Silicone Adhesives: RTV silicone adhesives are recommended for applications requiring moderate bond strength, a high service temperature, and thermal expandability. Silicone rubber adhesives may be used with all standard Lexan resins including glass-reinforced grades.

For optimum performance the following procedure is recommended:

- Lightly abrade mating surfaces with fine emery
- Clean surfaces of grease or foreign material with isopropyl alcohol
- Treat abraded surfaces with recommended primer and follow procedure recommended by manufacturer
- Apply silicone adhesive in desired thickness. Final bond thickness may range from 0.005 to 0.030 inches (0.13–0.76 mm) depending on joint design
- Assemble

Polyurethane Adhesives: Polyurethane adhesives are recommended for bonding Lexan resin to metal, glass, ceramics, and other plastics. These two-part adhesives are characterized by bonds which have excellent shear and lap strength, high impact resistance and excellent low-temperature performance. However, polyurethane adhesives are generally limited to service temperatures under 200°F (93°C). At temperatures above 200°F (93°C), tensile lap shear values may decline dramatically due to their low degree of cross-linking. They suffer somewhat from creep at room temperature and may exhibit undesirable changes in properties with aging. As such, they are not particularly suited to outdoor applications.

Other Adhesives: There are a number of one-part adhesive systems recommended for use with Lexan resin. One-part elastomers are available in a wide range of formulations. They provide quick tack and moderate to high shear strength.

Hot melts are easy-to-apply compositions which solidify rapidly, producing good adhesion. These adhesives are not recommended for joints under heavy loading or where use temperature exceeds 200°F (93°C). However, they are characterized by good water resistance. A likely application would be a water-resistant label.

Reference: *Lexan Design Guide*, Supplier design guide (CDC-536E), General Electric Company, 1986.

GE Plastics: Lexan GR1110 (features: gamma radiation stabilized)

Based on the results of a study to determine the effects of gamma radiation on adhesive bond strength, it was found that UV-curable adhesives were effective in securing Lexan GR1110 resin. After extremely high dosages of gamma radiation, 10 Mrads, the bond strength was not compromised. In all cases, the mode of failure was within the substrate, indicating that the material broke, not the bond joint. Therefore, the bond strength is greater than, or equal to the values reported.

Reference: *Guide to Engineering Thermoplastics for the Medical Industry*, Supplier design guide (MED-114), General Electric Company.

27.12 Mechanical Fastening

Bayer: Makrolon

Tapping and Self-Tapping Screws: Thread-forming screws do not have a cutting tip. They displace material in the plastic boss to create a mating thread. Because this process generates high levels of radial and hoop stress, avoid using these screws with less-compliant materials, such as Makrolon polycarbonate resins or polycarbonate blends. As an alternative, use thread-cutting screws for these materials.

Table 27.6 lists some average pull-out forces and various torque data for thread-cutting screws tested in Makrolon PC. For this data, the screws were installed in the manufacturer's suggested hole diameters. The screw boss outer diameter was approximately twice the screw's outer diameter.

Reference: *Engineering Polymers. Joining Techniques. A Design Guide*, Supplier design guide (5241 (7.5M) 3/01), Bayer Corporation, 2001.

Altuglas International: Tuffak (form: sheet)

Mechanical fastening is best for all high-impact situations. All fasteners must be clean of any cutting oil, which could cause crazing after assembly in a hole.

Threaded Fasteners: Threaded fasteners can use a predrilled hole, and the fastener cuts its own threads, or has a nut, such as through bolts. The hole may be prethreaded for machine screws or a threaded insert may be press-fitted or welded into a predrilled hole. Predrilled holes for self-tapping screws would have a diameter half-way between the root and outside diameter of the screw. Use a coarse thread, Type-25, for both screws and inserts. Inserts are chosen when frequent disassembly is anticipated, and cross-threading is likely. The material thickness must be great enough to allow at least four threads to be engaged. Vibrational service may rule out self-tapping screws, because high stresses can lead to cracks emanating from the hole. Fasteners hold better in holes pretapped in Tuffak, compared to threaded inserts. The joint, however, is not as strong, since plastic threads are susceptible to breaking and chipping and can be cross-threaded more easily. Metal inserts give the strongest joint, and the press-fit types hold well. Expansion-type inserts are stronger than press-fit. When predrilling for bolts, drill oversize to allow for ample clearance, since the hole will shrink more than the fastener under thermal contraction. A tight fit might crack the hole.

Permanent Fasteners: Tuffak polycarbonate permanent fasteners include some that cannot be used on other, more brittle materials and plastics. These include rivets, pins, staples, clinching fasteners, stitching, grommets, and eyelets. Because Tuffak polycarbonate is a notch-sensitive material, fasteners should not have sharp edges.

Speed rivets have two heads which fit inside each other to provide a longer-lasting joint. One-sided, blind rivets must have a washer on one side to prevent digging into the Tuffak polycarbonate surface. Rivets should be aluminum, or must use a soft washer to protect the soft Tuffak sheet surface. Snap-fits, if designed properly, can work well with Tuffak polycarbonate.

Table 27.6. Thread-cutting Screw Data for Makrolon 3200 Polycarbonate Resin

Screw Size & Type	Screw length, in. (mm)	Hole Diameter, in. (mm)	Drive Torque, lb in. (Nm)	Recommended Tightening Torque, lb in. (Nm)	Stripping Torque, lb in (Nm)	Screw Pull-Out, lb (N)
#6, Type-23	0.375 (9.5)	0.120 (3.0)	8 (0.9)	14 (1.6)	25 (2.8)	360 (1600)
#6, Type-25	0.500 (12.7)	0.120 (3.0)	6 (0.68)	16 (1.8)	30 (3.4)	568 (2528)
#6, Hi-Lo	0.750 (19.0)	0.115 (2.9)	5 (0.56)	14 (1.6)	30 (3.4)	668 (2973)
#8, Type-23	0.500 (12.7)	0.146 (3.7)	9 (1.0)	21 (2.4)	38 (4.3)	556 (2474)
#8, Type-25	0.562 (14.3)	0.146 (3.7)	18 (2.0)	28 (3.0)	50 (5.6)	884 (3934)

They have low creep characteristics compared to other plastics, and maintain the required interference over a long time.

Reference: *Tuffak Polycarbonate Sheet. Forming and Fabrication*, Supplier design guide (ADV980496/APL:ATG-16S/web/6-00), Altuglas International, 2000.

Polycarbonate

Staking: Staking is a common application for ultrasonic assembly. The process works well with soft or amorphous materials with relatively low melt flows. These materials allow the head of the rivet to be formed by both mechanical and thermal mechanisms. If materials with high melt flows or materials that require relatively high vibrational amplitudes are used, the melt tends to flow so rapidly and uncontrollably that material is ejected out of the horn contour. The loss of material results in an incomplete rivet head.

Amplitude modification was used to improve the control of the melt flow. High amplitude was used to initiate the melt of the plastic, then reduced to limit the flow while maintaining the heat.

Reference: Grewell DA, Frantz JL: Amplitude control in ultrasonic welding of thermoplastics. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

Dow Chemical: Calibre (features: transparent)

With some considerations, parts made of Calibre polycarbonate lend themselves to all mechanical assembly methods.

Rivets: Rivets can be used to assemble Calibre polycarbonate to itself, to metals, or to other plastics. Use rivets made of aluminum, because of this metal's ability to deform under load (which limits the compressive forces imparted during the riveting process) and because the coefficients of thermal expansion of aluminum and polycarbonate are similar. As with most mechanical assemblies, incorporating a washer to distribute the loading over a larger area is advisable.

Snap-fit Assemblies: Calibre polycarbonate is especially well-suited for cantilever snaps because of its consistent, low mold shrinkage, its high resistance to creep, and its overall dimensional stability. The permissible strain for Calibre polycarbonate during a single, brief snap-fit is 4%. If frequent assembly and disassembly are anticipated, the strain level should be reduced to about 60% of that value, or 2.4%.

Press-fit Assemblies: When designing a press-fit, make sure the design provides holding strength adequate to meet the assembly requirements without overstressing the assembly. This potential problem is complicated by three factors:

- Press-fit designs require close manufacturing tolerances
- Calibre polycarbonate is a rigid material
- Part dimensions will change with time due to creep and relaxation

In designing a press-fit between two parts made of rigid materials, minimize the interference between the two parts to keep the assembly stresses at acceptable levels (Fig. 27.5).

Creep is the change in dimensions of a molded part resulting from cold flow incurred under continued loading. Creep can cause a press-fit that was considered satisfactory at the time of assembly to loosen to an unacceptable condition or even to failure. A standard method of overcoming this problem is to incorporate grooves on the shaft. This reduces the assembly stresses, and thereby the degree of creep. After assembly, and over time, the plastic will cold-flow into the grooves and retain the desired holding strength of the fit.

Staking: Because of the high degree of stiffness of Calibre polycarbonate, and because of the extremely

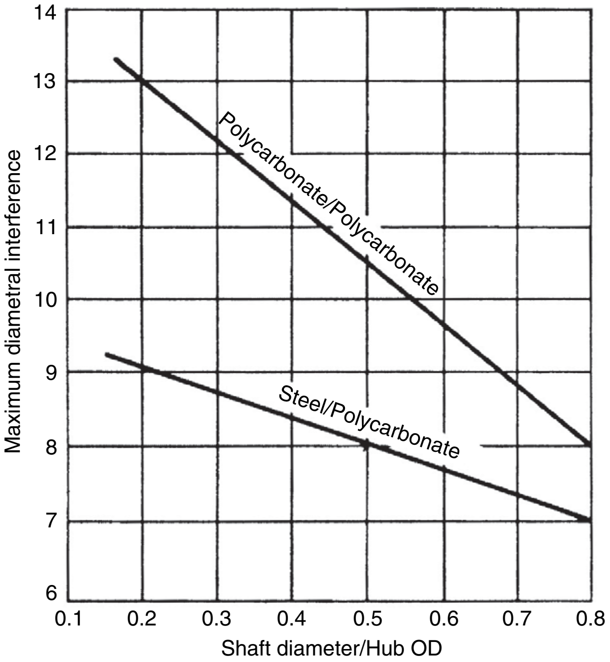


Figure 27.5. Recommended diametral interference @ 23°C (73°F), for interference fits in Calibre polycarbonate resins.

high residual stresses of the staking process, cold staking generally is not an acceptable assembly method.

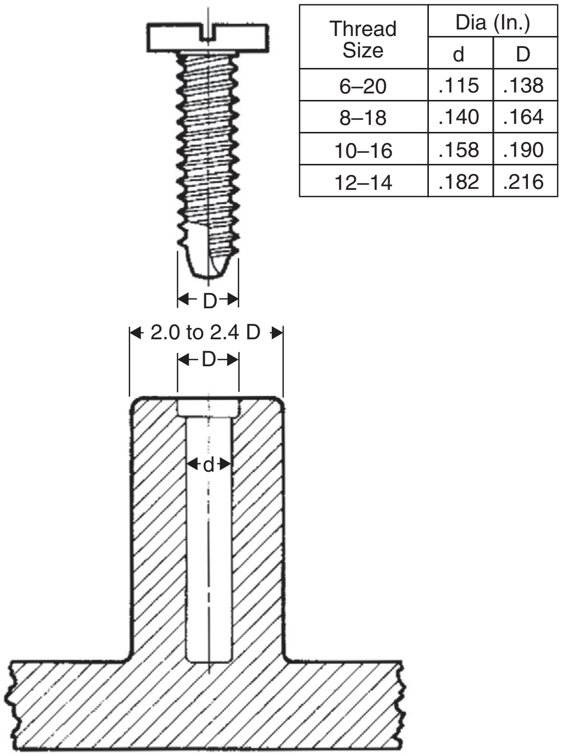
Screws: Like metals and many other plastics, Calibre polycarbonate accommodates many types of screw assemblies. The four major methods are: to screw directly into the Calibre polycarbonate part, using self-threading screws; to screw into a threaded insert that is incorporated within the part; to pass the screw through the part and secure it with an external nut or clip; and to mold threads into or onto the Calibre polycarbonate.

Tapping and Self-tapping Screws: There are two types of self-threading screws—thread-forming and thread-cutting. Thread-forming screws are not recommended for use with Calibre polycarbonate because they induce high stresses into the plastic as the thread is formed. Thread-cutting screws (such as Type-23 or -25) are recommended because they form threads by actually cutting away the plastic material, inducing minimal deformation and reducing hoop stress. Flat head screws should be avoided because the wedging action causes high hoop stress.

If the unit is to be repeatedly assembled and disassembled, use Type-23 screws. If a self-tapping screw is removed from an assembly, always replace it with a standard-pitch machine screw for reassembly. Otherwise, the self-tapping screw may cut a new thread over the original thread, resulting in a stripped thread. This assembly method allows for only a minimum number of disassemblies and reassemblies; repeated removal and return of the screw decreases the strength of the material. For applications requiring frequent reassembly, ultrasonically applied metal inserts are suggested.

The following comments are applicable to boss design for self-threading screws in Calibre polycarbonate (Fig. 27.6):

- Entry counterbore diameter should be equal to the major diameter (D) of the screw thread and approximately equal to a depth of one pitch length.
- Inside diameter of the boss (d) should be equal to the pitch diameter of the screw thread.
- Outside diameter of the boss should be 2.0–2.5 times the major diameter (D) of the screw thread.
- Minimum thread engagement should be 2.5 times the pitch diameter.
- Boss height must result in an assembly that supplies direct, flush, continuous support to the screw. The design may include a washer and/or spacer to accomplish this.



Thread Size	Dia (In.)	
	d	D
6–20	.115	.138
8–18	.140	.164
10–16	.158	.190
12–14	.182	.216

Figure 27.6. Recommended boss design for self-threading screws in Calibre polycarbonate.

- Either a through hole or blind hole in the boss will provide adequate melt flow. Bottom thickness of a blind hole should be equal to nominal wall thickness.

Screws with Nuts: Screws that pass through the plastic part and are retained by an external nut or clip provide a simple, convenient assembly method. This method lends itself to multiple reassemblies and is unaffected by the amount of torque that is applied to the plastic. Good design for this assembly method requires attention to the following (Fig. 27.7):

- Design the joint area to eliminate any space between the two plastic surfaces being assembled. This puts the assembly in compressive loading instead of tensile loading, reducing tensile stresses that can cause failure. A spacer may be needed to accomplish this.
- Use a washer to distribute the high torque loading over a greater surface area.

Molded-in Threads: Most standard thread designs can be molded into Calibre polycarbonate. There are only three limitations. First, avoid extra fine threads. These are difficult to fill, and usually are not strong

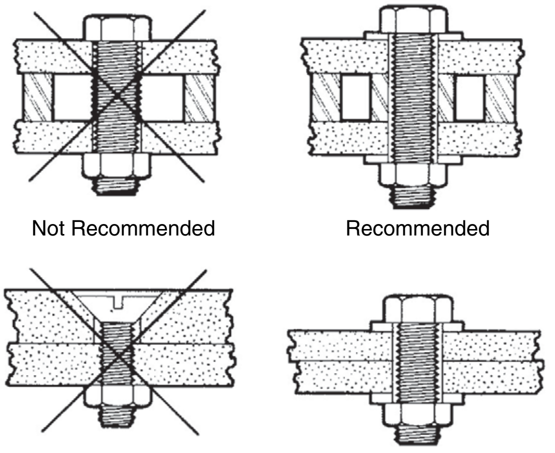


Figure 27.7. Assembly design for screws with nuts using Calibre polycarbonate.

enough to withstand torque requirements. Second, threads should not have sharp corners. These can form notches and decrease the screw-retention values. Third, threads should always have a radius at the root to avoid stress concentrators.

The following dimension guidelines should be helpful in designing molded-in threads (Fig. 27.8):

- Avoid running threads out to the edge of the screw base. Leave a gap of approximately 0.030 inches (0.76 mm).
- The minimum active thread length should be 1.5 times the pitch diameter of the thread.
- The minimum wall thickness around the internal thread should be 0.5 times the major diameter of the thread.
- Avoid the use of tapered pipe threads. As the threaded article is increasingly tapered, the hoop stress increases.

Threaded Inserts: Threaded inserts, commonly made of nonferrous metal, are utilized in several designs. They can be built into the plastic part as molded-in inserts, heat or pressure inserts, ultrasonic inserts, or expansion inserts. The preferred method for embedding the insert into Calibre polycarbonate is ultrasonic insertion, because it imparts low residual stresses, and is inexpensive. The least preferred method, because of the high residual stresses that result, is expansion insertion.

For good design, inserts should not have sharp corners or edges that could act as notches or stress concentrators. An undercut with a flat or smooth knurl minimizes notch sensitivity and still provides acceptable pull-out and torque levels.

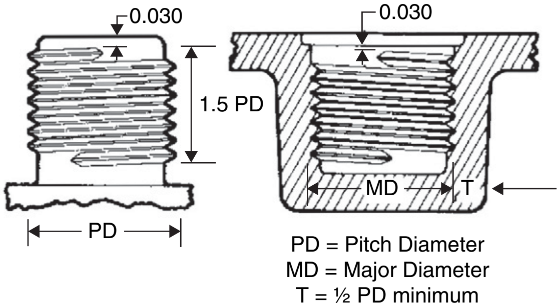


Figure 27.8. Recommended design for molded-in threads, Calibre polycarbonate.

Reference: *Calibre Engineering Thermoplastics Basic Design Manual*, Supplier design guide (301-1040-1288), Dow Chemical Company, 1988.

Bayer: Makrolon

Tapping and Self-tapping Screws: Any part mounted to another by means of a self-tapping screw must be located flush with the top of the boss. Eventually, a spacer must be used. Otherwise, the screw will be pulled out and the cut-in thread destroyed or even breakage of the boss may occur.

Data concerning the holding load or the stripping force for self-tapping screws, which can be found in the literature, are often irrelevant. They are results from short-term testing, but do not consider the long-term behavior of the material and its creep. The respective load would lead to failure, generally by breakage of the boss within a short period of time.

Molded-in Threads: Unified and American Standard screw threads, injection molded, must be judged very carefully. The threads, forming a number of pronounced notches, reduce the impact strength and the ultimate elongation under tensile stress significantly. Trapezoidal and knuckle threads are better to a certain degree. Preferably, screw and nut, or threaded holes should be of polycarbonate, and no higher load applied. The used length of the thread must be more than 1.5 times the diameter; the section thickness around the hole more than 0.6 times the diameter.

Avoid feather edges, and limit the tightening with a shoulder of the bolt.

Reference: *Makrolon Polycarbonate Design Guide*, Supplier design guide (55-A840(10)L), Bayer, 1988.

Bayer: Makrolon

Riveting: With Makrolon polycarbonate, care must be exercised to minimize stresses induced during the fastening operation. To distribute the load, rivets with large heads (three times the shank diameter) should be used with washers under the flared end of the rivet. The rivet setting tool should be calibrated to the correct length to control the compressive stress applied to the joint area.

Snap-fit Assemblies: Snap-fits are a simple, economical, and rapid way of joining components manufactured from Makrolon polycarbonate. Many different designs and configurations can be utilized with this joining technique. The permissible strain for a one-time snap-fit assembly in Makrolon polycarbonate is 4%. For repeated assembly, the maximum strain should be reduced to 2.4%.

Press-fit Assemblies: Press-fits are occasionally used in Makrolon polycarbonate applications. Because this procedure involves high stresses, the fit must be designed with care (Figs. 27.9 and 27.10). Following are some points to keep in mind with press-fits:

- Be sure all parts are clean and free of any foreign substance.
- Press-fits of unlike materials should be avoided if they are subject to thermal cycling.
- Avoid press-fits if the assembly is subject to a harsh environment.

Tapping and Self-Tapping Screws: Thread-cutting screws like the Type-23, Type-25, and the Hi-Lo (with a cutting edge on the point) actually remove material as they are installed, avoiding high stress build-up. Thread-cutting screws can cause problems if they are removed and reinstalled repeatedly, because each time they are reinstalled new threads can easily be cut. If repeated assembly is required, Type-23 screws should be replaced with a standard machine screw to avoid recutting of threads. This cannot be done with a Type-25 screw because it has a nonstandard thread pitch.

As with common threaded fasteners, flat-head screws should be avoided.

Screw bosses should be designed very carefully. While small boss diameters reduce the tendency for sinks and/or voids, they might not provide sufficient structural integrity to withstand assembly hoop stress.

Molded-in Inserts: Metal inserts can be molded in Makrolon polycarbonate, but problems can result with this technique. Because Makrolon polycarbonate has a much higher coefficient of thermal expansion than metal, molded-in inserts should be avoided for applications subject to thermal cycling. Glass-reinforced grades of Makrolon polycarbonate that have thermal coefficients closer to metals are less likely to cause problems.

Inserts that weigh more than 0.05 oz (1.5 g), or are 0.250 inches (6.35 mm) in diameter or larger, should be preheated to about 350–400°F (177–204°C) prior to insertion in the mold. This will help to reduce thermal stresses caused by the hot melt contacting the cold metal insert.

Before inserts are placed in the mold, they should be free of all foreign matter. Care must be exercised to see that the insert seats securely to prevent floating which can cause extensive mold damage.

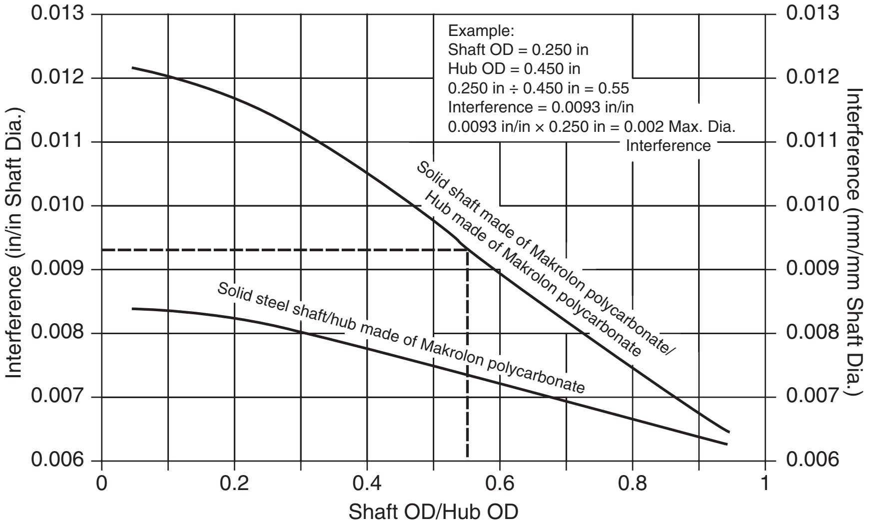


Figure 27.9. Maximum diametral interference for Makrolon polycarbonate and steel press-fits (solid shafts).

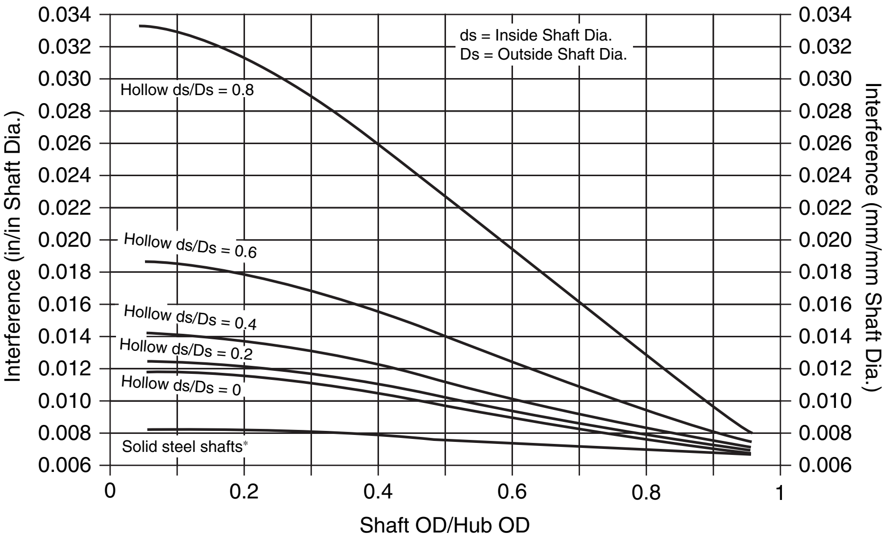


Figure 27.10. Maximum diametral interference for Makrolon polycarbonate and steel press-fits (hollow shafts).

Inserts with sharp knurls or protrusions can have high pullout values, but they can also reduce impact values because the sharp points cause a notch effect.

Molded-in Threads: When the application involves infrequent assembly, molded-in threads can be used. Coarse threads can be molded in Makrolon polycarbonate more easily than fine threads. Threads of 32 or finer pitch should be avoided, along with tapered threads (e.g., pipe threads), which are not recommended because they can cause excessive stress.

The following factors also should be considered:

- If the mating part is metal, over torquing will result in part failure.
- Feather edges on thread runouts should be avoided to prevent cross threading or thread damage.
- The roots and crests of threads should be rounded to reduce stress concentrations as well as to help mold filling.
- Internal threads can be formed by collapsible cores or unscrewing cores. External threads are formed by split cores or unscrewing devices. All of these increase mold costs.

Threaded Inserts: Inserts ultrasonically installed in Makrolon polycarbonate provide an excellent base for threaded fasteners. When done correctly, a problem-free joint can be expected.

In general, optimum insert performance may be achieved when the boss OD is two times the insert diameter. The receiving hole, which can be straight or have an 8° taper, as some inserts require, is usually 0.015–0.020 inches (0.38–0.51 mm) smaller than the insert OD. The hole should be deeper than the insert length so that the insert will not bottom out and to provide a well for any excess plastic melt.

When installed, the top of the insert should be flush or slightly above—0.0003 inches (0.01 mm)—the top surface of the boss. If the insert is below this surface, jackout of the insert can occur.

Reference: *Makrolon Polycarbonate—A Guide for Joining Techniques*, Supplier design guide (55-A664(10)C), Bayer, 1987.

GE Plastics: Lexan

Riveting: Care should be taken when riveting Lexan resin to avoid the high stresses inherent in most riveting techniques. Using a shouldered rivet limits the amount of stress imposed on the part (Fig. 27.11). Aluminum rivets also limit the force that can be applied, since the aluminum will deform under high stress.

In general, the rivet head should be 2.5–3 times the shank diameter, and the flared end of the rivet should have a washer to avoid high, localized stresses. Clearance around the shaft should allow easy insertion, but should not be so great as to allow slippage of the joined parts.

Press-fit Assemblies: Press-fit inserts can be used with Lexan resin to fasten two parts together. However, since this is a very high stress fastening technique, care must be taken to remain under the creep limit, and it should be remembered that high stresses leave the part more susceptible to chemical and thermal attack.

The following precautions must be observed in order to avoid over-stressed conditions:

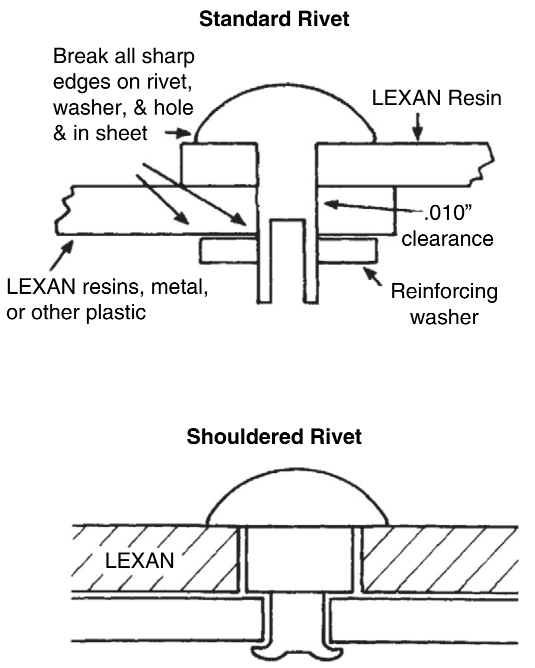


Figure 27.11. Standard rivet and shoulder rivet design for Lexan polycarbonate.

- Design press-fit equal to/or less than the creep limit.
- Use smooth, rounded inserts because of the possible stress concentration created by a knurl.
- Avoid locating a knit line on the area to be inserted.
- Remove all incompatible chemicals from the insert.

A change in operating temperature and dissimilar coefficients of thermal expansion can affect the amount of stress around the shaft. Press-fits should be designed for anticipated operating conditions, while keeping in mind the environment and other potential conditions to which the part may be exposed.

Staking: In ultrasonic staking, tip configuration of the horn will depend upon the application, the grade of resin, and the stud configuration. Rigid support of the Lexan resin part is necessary during the staking operation.

Screws: Machine screws are commonly used to assemble components made of Lexan resin. When machine screws are engaging Lexan resin threads, torque specification is a function of:

- Bearing force of the screw head or washer
- Thread shear stress
- Boss tensile stress

Tapping and Self-tapping Screws: Self-tapping screws of the thread-cutting variety perform satisfactorily in parts molded from Lexan resin, with Type-25 or -23 recommended because they cut a clean thread with negligible material deformation. Thread-forming screws should be avoided because of the high induced stress developed by the forming operation of the thread.

Generally, the designer should follow these recommendations in planning for self-tapping screws:

- The receiving hole diameter should be equal to the screw pitch diameter.
- The boss outside diameter (OD) should be strong enough to withstand possible hoop stresses developed by screw insertion. Usually, a boss OD equal to twice the screw major diameter is sufficient.
- A length at least twice the screw major diameter should be provided for thread engagement.
- Repeated assembly operations should be avoided.
- Use the minimum torque possible to keep screw assembly stress within the design limit of Lexan resin.

Self-tapping screws should not be used when repeated disassembly may occur. Unless extreme care is taken, a second insertion can result in the cutting of a second set of threads. This greatly weakens the structure, and may reduce torque retention to near-failure levels. If repeated removal and insertion is unavoidable, a Type-23 screw should be used initially, then replaced with a standard machine screw; an insert is best when repeated assembly is anticipated.

The amount of torque that can be placed on a screw depends on both the cross-sectional area of the boss and the total number of threads. Since sufficient threads can usually be provided, allowable torque is most often dependent on boss cross-section.

Molded-in Inserts: Molded-in inserts are not recommended for use with unreinforced Lexan resins (particularly in applications exposed to thermal cycling). They may perform adequately with glass-reinforced grades of Lexan resin, because of the lower coefficient of thermal expansion and high design stress limit. Although ultrasonic inserts are better alternatives than molded-in inserts, lack of facilities and experience result in many molders preferring molded-in inserts.

A simple pull-out or torque retention groove, or a flat surface on one or two sides of an insert may prove to provide sufficient torque and pull-out strength. Knurled inserts should be avoided because they can produce a notch effect in the material. Since molded-in inserts will cause stresses in the Lexan resin around them, parts should be tested under the end-use environment to evaluate the strength of the inserts.

Ultrasonic Inserts: Ultrasonic insertion is a fast, economical method of embedding metal inserts into parts molded from Lexan resin. This technique offers a high degree of mechanical reliability with excellent pull-out strength and torque retention, combined with savings resulting from rapid production cycles. If the assembly is properly designed, ultrasonic insertion results in a lower residual stress compared to molded-in or pressed-in techniques. This is because a thin film of homogeneous melt occurs around the insert.

For most applications, the ultrasonic energy should be transferred through the metal insert. Due to the wear on the horn as metal touches metal during the insertion process, steel horns are usually recommended. Since steel horns cannot be driven at high amplitudes, a low amplitude is usually used for insertion. In some cases, the horn can make contact with the Lexan resin. Experimentation will quickly determine the preferred medium for energy transfer in a specific application. A part must be rigidly supported during the insertion operation.

Self-tapping Inserts: As with self-tapping screws, self-tapping inserts with self-cutting Type-25 threads are recommended for use with Lexan resin parts. These inserts are able to withstand the same amount of longitudinal loading as a screw of the same outer diameter, since loading is a function of the shear area present around the insert. Generally, material thickness around the insert should be at least 90% of the outer radius of the insert.

Reference: *Lexan Design Guide*, Supplier design guide (CDC-536E), General Electric Company, 1986.

28 Polyesters

28.1 Polyethylene Terephthalate

28.1.1 General

Ticona: Impet

Impet moldings can be joined by ultrasonic, vibration, spin or hot plate welding, depending on the joint geometry and type of application. In hot plate welding, because of the strong tendency of the melt to stick to the hot plate, contactless radiant heating is preferable. For prototype construction, hot gas welding with a welding rod may also be employed.

Reference: *Celanex, Impet, Vandar Thermoplastic Polyesters*, Supplier design guide, Ticona, 2001.

28.1.2 Ultrasonic Welding

Eastman Chemical: Eastar

The following guidelines are suggested for obtaining the best ultrasonic welds:

- Use parts that are fully packed and have flat, parallel surfaces.
- Low weld pressure and high weld time give the strongest welds. Hold time has no significant effect on weld strength.
- In a tongue and groove joint design, energy directors, either in the form of a criss-cross pattern or single ridge, give the best results.
- Smooth and textured surfaces with no energy director generally result in the weakest welds.

Reference: Moskala EJ, Eiselstein BT, Morrow MC, Free DA: Ultrasonic welding of copolyester resins. ANTEC 2003, Conference proceedings, Society of Plastics Engineers, Nashville, May 2003.

DuPont: Rynite

Because of its high stiffness, this glass-reinforced polyester resin is easy to weld. It is preferable to always use a step joint for such a resin, which is often used in very demanding applications (sometimes even at high temperatures). An over-welding time may generate burned material in the sonotrode area.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I*, Supplier design guide, DuPont Company, 2002.

28.1.3 Hot Gas Welding

Eastman Chemical: Spectar (features: PETG copolyester; form: sheet)

Technology has been developed that allows plastic sheet fabricators to obtain clear, strong bonds by welding with a rod of sheet made with Spectar copolyester material.

Reference: *Fabricating and Forming Sheet Made with Spectar Copolyester*, Supplier design guide (TRS-194G), Eastman Chemical Company, 2003.

28.1.4 Laser Welding

Eastman Chemical: Eastar GN007 (features: PETG copolyester; form: AWS ultrasonic test speicmens)

Scanning laser welding was carried out using a diode laser with the following parameters:

- Wavelength: 940 ± 10 nm.
- Maximum output power: 300 W continuous.
- Beam size: 2.0 × 2.0 mm (0.08 × 0.08 inches).
- Maximum speed: 10,000 mm/s (33 ft/s).

The laser absorber was Clearweld material system LD130D, which was liquid-dispensed onto the top surface of the bottom part. Samples were welded using a single beam contour method and a quasi-simultaneous method to compare weld strengths and collapse.

Fast welding speeds were achievable with contour welding. Higher strengths were achieved with single beam contour welding than quasi-simultaneous. A maximum collapse of 0.63–0.67 mm (0.025–0.026 inches) was achieved with both methods under the conditions evaluated. Collapse was detrimental only at 300 W, pressure of 9.1 MPa (1320 psi) and weld speeds less than 65.2 mm/s (2.6 inches/s).

Reference: Woosman NM, Burrell MM: Evaluating quasi-simultaneous and contour welding for use with the Clearweld™ process. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

DuPont: Rynite

Rynite has low transparency to laser radiation, and therefore needs high laser powers to achieve a weld.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I*, Supplier design guide, DuPont Company, 2002.

28.1.5 Solvent Welding

Eastman Chemical: Spectar (features: PETG copolyester; form: sheet)

There are several options for solvent welding sheet made with Spectar copolyester to itself. These include commercial products as well as custom blends of MEK and methylene chloride. MEK , a fast-acting solvent, gives quicker set-up with more likelihood of freeze-off (setting up before the joint is filled). Methylene chloride, on the other hand, is a slower solvent and offers more work time with less potential for freeze-off. In some locations, a 50:50 mix of methylene chloride and MEK is used as a starting point to formulate custom solvent blends. A small amount of acetic acid can be added when bonding in humid environments.

Some water-thin formulas designed for welding acrylics can also be used to weld sheets made from Spectar copolyester to itself, if they are used with care. Weld-On 3 and Weld-On 4, available from IPS Corporation, are two such formulas. Hazing may, however, occasionally be a problem.

Do not use thick cements intended for use with other plastics; they are generally incompatible with sheets made from Spectar copolyester.

Reference: *Fabricating and Forming Sheet Made with Spectar Copolyester*, Supplier design guide (TRS-194G), Eastman Chemical Company, 2003.

Ticona: Impet

Because of Impet's good solvent resistance, solvent bonding is not recommended.

Reference: *Celanex, Impet, Vandar Thermoplastic Polyesters*, Supplier design guide, Ticona, 2001.

28.1.6 Adhesive Bonding

Hoechst Celanese: Resin T80

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 28.1 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually as shown in Table 28.1 so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 and Super Bonder 414 instant adhesives and Flashcure 4305 light

Table 28.1. Shear Strengths of Hoechst Celanese Resin T80 PET to PET Adhesive Bonds Made Using Adhesives Available from Loctite Corporation.[b]

Material composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive Rubber Toughened)	**Prism 401** (Instant Adhesive Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive General Purpose)	**Depend 330** (Two-Part No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	7 rms	450 (3.1)	>3200[a] (>22.1)[a]	>1800[a] (>12.4)[a]	>2200[a] (>15.2)[a]	500 (3.5)	1150 (7.9)
Roughened	31 rms	200 (1.4)	900 (6.2)	700 (4.8)	950 (6.6)	500 (3.5)	1150 (7.9)
Impact modifier	17% Novalene 7300P	>250[a] (>1.7)[a]	>350[a] (>2.4)[a]	>250[a] (>1.7)[a]	>400[a] (>2.8)[a]	>150[a] (>1.0)[a]	>300[a] (>2.1)[a]
Flame retardant	15% PO-64P 4% Antimony Oxide	1550 (10.7)	>2150[a] (>14.8)[a]	600 (4.0)	>2200[a] (>15.2)[a]	850 (5.9)	1150 (7.9)
Lubricant	0.2% Zinc Stearate	750 (5.2)	>1800[a] (>12.4)[a]	>1800[a] (>12.4)[a]	>2200[a] (>15.2)[a]	500 (3.5)	1150 (7.9)
Internal mold release	0.5% Mold Wiz 33PA	800 (5.5)	>3200[a] (> 22.1)[a]	>1800[a] (>12.4)[a]	>2200[a] (>15.2)[a]	500 (3.5)	1700 (11.7)
Filler	17% 3540 Fiberglass	800 (5.5)	2900 (20.0)	>3350[a] (>23.1)[a]	2200 (15.2)	800 (5.5)	1700 (11.7)
Colorant	0.5% Green 99-41042	1000 (6.9)	>2200[a] (>15.2)[a]	>1800[a] (>12.4)[a]	>2200[a] (>15.2)[a]	500 (3.5)	1150 (7.9)
Antistatic	1% Dehydat 8312	>1350[a] (>9.3)[a]	>1900[a] (>13.1)[a]	>1800[a] (>12.4)[a]	>1450[a] (>10.0)[a]	500 (3.5)	1150 (7.9)

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

cure adhesive created bonds that were stronger than the PET substrate for most of the formulations tested. Loctite 3105, a light curing acrylic adhesive, and Hysol 3631 hot melt adhesive achieved the second highest bond strengths. Loctite 3340 light cure adhesive, a UV cationic epoxy, and Hysol 7804 hot melt adhesive achieved the lowest bond strengths.

Surface Treatments: The overall effect of using Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, on PET could not be determined as most of the PET formulations evaluated achieved substrate failure for both the primed and unprimed PET. However, the use of Prism Primer 770 or 7701 did cause a statistically significant increase in the bondability of glass filled PET, and a statistically significant decrease in the bondability of flame retarded PET. Surface roughening had no effect with the acrylic adhesives and had a negative effect with the cyanoacrylate adhesives.

Other Information: PET is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

Eastman Chemical: Spectar (features: PETG copolyester; form: sheet)

Adhesive bonding can be used to bond sheet made from Spectar copolyester to other materials such as acrylic or polycarbonate.

For bonding sheet made with Spectar copolyester to itself, use Weld-On 58, Weld-On 55, Weld-On 42 from IPS Corporation; Scotch-Weld DP-100 from 3M; Durabond 105CL, Light Cure 3104, Light Cure 3105 from Loctite; Ultra Light-Weld 3072 from Dymax or Plastic Welder II from Devcon.

For bonding sheet made with Spectar copolyester to sheet of acrylic, use Weld-On 42 from IPS Corporation; Durabond 105CL, Light Cure 3104, Light Cure 3105 from Loctite; Ultra Light-Weld 3072 from Dymax or Plastic Welder II from Devcon.

For bonding sheet made with Spectar copolyester to sheet of polycarbonate, use Weld-On 58, Weld-On 55 from IPS Corporation; Durabond 105CL, Light Cure 3104, Light Cure 3105 from Loctite; Ultra Light-Weld 3094, Ultra Light-Weld 3072 from Dymax or Plastic Welder II from Devcon.

Reference: *Fabricating and Forming Sheet Made with Spectar Copolyester*, Supplier design guide (TRS-194G), Eastman Chemical Company, 2003.

Ticona: Impet

For bonding Impet, two-pack adhesives based on epoxy resins, polyurethanes or silicone resins are recommended. Depending on the application, cyanoacrylate or hot melt adhesives may also be used.

Reference: *Celanex, Impet, Vandar Thermoplastic Polyesters*, Supplier design guide, Ticona, 2001.

BIP Chemicals: Beetle

Moldings may be joined by the use of adhesives. Epoxy and cyanoacrylate adhesives are particularly effective. To obtain optimum bond strength, the contact surfaces should be degreased with acetone and roughened prior to bonding.

Reference: *Beetle & Jonylon Engineering Thermoplastics*, Supplier marketing literature (BJ2/1291/SP/5), BIP Chemicals Limited, 1991.

DuPont: Rynite

Parts or stock shapes such as plaques of Rynite can be bonded to each other by the use of commercially available adhesives. A list of adhesives that have been tested with successful results in bonding Rynite to Rynite are listed in Table 28.2. For best results, the surfaces should be cleaned with a solvent such as acetone prior to applying the adhesive.

Table 28.2. Adhesive Recommendations for Bonding Rynite Polyester PET to Itself

Supplier	Adhesive Number	Adhesive Type
H.B. Fuller	UR 2139	Polyurethane
3M	Scotchweld 2214	Epoxy
Armstrong	A-12	Epoxy
Loctite	Hysol 9412	Epoxy
Loctite	Super Bonder 430, 496, 414	Cyanoacrylate
Permabond	102,105,747	Cyanoacrylate
3M	Scotchweld CA-40	Cyanoacrylate

One of the many uses of adhesive bonding is the joining of plaques to form a thick section for machining of prototypes. Polyurethane adhesives have been used successfully in this manner, and parts produced have survived severe end-use testing conditions such as automotive under hood environments. Plaques bonded with adhesive should be annealed, rough machined, and annealed again prior to final machining. Annealing conditions are one to two hours at 149°C (300°F) in air.

Reference: *Rynite Design Handbook for DuPont Engineering Plastics*, Supplier design guide (E-62620), DuPont Company, 1987.

28.1.7 Mechanical Fastening

Eastman Chemical: Spectar (features: PETG copolyester; form: sheet)

Because of its outstanding toughness, sheets made with Spectar copolyester adapt to mechanical fastening readiliy. Screws designed specifically for plastics should be used. Holes should be drilled slighly oversized to allow for thermal expansion and contraction. Drilled holes should have smooth edges. Washers should be used for better load distribution. The use of flexible washers is preferred.

Fasteners should not be overtightened. Self-tapping screws should not be used to hang large panels.

Reference: *Fabricating and Forming Sheet Made with Spectar Copolyester*, Supplier design guide (TRS-194G), Eastman Chemical Company, 2003.

DuPont: Rynite

Self-tapping Screws: For Rynite PET-reinforced resins, the finer threads of the Type-T screw are recommended. Even with the fine pitch screws, backing out the screw will cause most of the threads in the plastic to shear, making reuse of the same size screw impossible. If fastener removal and replacement is required in this group of materials, it is recommended that metal inserts be used, or that the boss diameter be made sufficiently larger to accommodate the next larger diameter screw.

Tables 28.3 and 28.4 give the numerical values of the pull-out strengths, stripping torque and dimensions for Type-AB screws of various sizes.

Snap-fits: The suggested allowable strains for lug type snap-fits are given in Table 28.5.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I*, Supplier design guide, DuPont Company, 2002.

Ticona: Impet

Impet moldings can be joined to each other or to articles made from different materials by conventional methods such as riveting, flanging or staking, or by using metal threaded inserts designed for ultrasonic or heat installation in the plastic. Mechanical assembly with screwed, snap-fit or press-fit joints is also an option, and offers the advantage of detachable joints in some cases. Assembly with spring clamps is also possible.

Reference: *Celanex, Impet, Vandar Thermoplastic Polyesters*, Supplier design guide, Ticona, 2001.

28.2 Polybutylene Terephthalate

28.2.1 General

Ticona: Celanex, Vandar

Celanex and Vandar moldings can be joined by ultrasonic, vibration, spin or hot plate welding,

Table 28.3. Pull-out Load Performances for Various Screw Dimensions in Rynite Resins

		Screw No.	6	7	8	10	12	14
		D_s (mm)	3.6	4.0	4.3	4.9	5.6	6.5
		d_s (mm)	2.6	2.9	3.1	3.4	4.1	4.7
		D_h (mm)	8.9	10.0	10.8	12.2	14.0	16.2
		d_h (mm)	2.9	3.3	3.5	4.1	4.7	5.5
Pull-out force	Rynite 530	N	3300	4100	4400	4900	*	*
	Rynite 545	N	4300	4470	4500	5660	6020	*
	Rynite 555	N	2480	2940	2740	3780	4120	*

D_s: major diameter of screw thread; d_s: pitch diameter of screw; $D_{h:}$ boss outside diameter; $d_{h:}$ boss hole diameter.
*Hub fracture under the screw.

Table 28.4. Stripping Torque Performances for Various Screw Dimensions in Rynite Resins

		Screw No.	6	7	8	10	12	14
		D_s (mm)	3.6	4.0	4.3	4.9	5.6	6.5
		d_s (mm)	2.6	2.9	3.1	3.4	4.1	4.7
		D_h (mm)	8.9	10.0	10.8	12.2	14.0	16.2
		d_h (mm)	2.9	3.3	3.5	4.1	4.7	5.5
Stripping torque	Rynite 530	Nm	3.3	4.3	4.6	7.2	–	–
	Rynite 545	Nm	4.7	5.1	5.3	8.6	10.4	11.8
	Rynite 555	Nm	4.3	4.7	4.2	6.0*	6.6*	9.8*

D_s: major diameter of screw thread; d_s: pitch diameter of screw; D_h: boss outside diameter; d_h: boss hole diameter.
*For these sizes d_h was increased by 10% to avoid hub fracture at the weld line.

Table 28.5. Suggested Allowable Strains for Lug Type Snap-fits in Rynite GR

	Allowable strain (%)	
Material	**Used once (new material)**	**Used frequently**
Rynite GR	1.0	0.5

depending on the joint geometry and type of application. In hot plate welding, because of the strong tendency of the melt to stick to the hot plate, contactless radiant heating is preferable. For prototype construction, hot gas welding with a welding rod may also be employed.

Reference: *Celanex, Impet, Vandar Thermoplastic Polyesters*, Supplier design guide, Ticona, 2001.

Degussa AG: Vestodur

All established types of welding technologies can be applied on Vestodur, with the exception of high frequency welding. Typical technologies used are hot plate welding, ultrasonic welding, and friction welding (by rotation or vibration).

Reference: *Vestodur Handling and Processing*, Supplier technical report (01/te/1000e), Degussa AG.

Huls AG: Vestodur

Vestodur grades reinforced with glass fibers or micro glass beads and/or containing a flame retardant are best welded using ultrasonic, vibration, or spin welding.

Reference: *Huls Vestodur Polybutylene Terephthalate*, Supplier technical report (42.01.003e/505.93/bu), Huls Aktiengesellschaft, 1993.

BASF AG: Ultradur

Ultradur can be welded by heated tool, friction and ultrasonic techniques. High frequency welding cannot be used because of the low dissipation factor.

Reference: *Ultradur Polybutylene Terephthalate (PBT) Product Line, Properties, Processing*, Supplier design guide (B 575/1e– (819) 4.91), BASF Aktiengesellschaft, 1991.

Hoechst AG: Celanex

With an increasing content of reinforcing materials, flame retardants or other modifiers, the welding properties of Celanex can be adversely affected. Potential reductions in quality may in some cases be countered by design measures such as widening the joint area.

Reference: *Celanex Polybutylene Terephthalate (PBT)*, Supplier design guide (BYKR 123 E 9070/014), Hoechst AG, 1990.

Bayer: Pocan B1505 (features: general purpose grade, unfilled); **Pocan B3235** (features: natural resin; material composition: 30% glass fiber reinforcement); **Pocan B4235** (features: flame retardant; material composition: 30% glass-fiber reinforcement)

There are certain basic differences related to the welding method used and the type of Pocan resin (Table 28.6). Tests have shown that unreinforced Pocan resin components can be satisfactorily joined by means of hot gas or heated tool welding. The greater the content of glass fiber and fire retardants, however, the weaker the weldlines are.

Reference: *Pocan Thermoplastic PBT Polyester—A General Reference Manual*, Supplier design guide (55-B635(7.5)J), Mobay Corporation, 1985.

Table 28.6. Guidelines for Use of Different Welding Techniques with Bayer Pocan B Polyester PBT

	Pocan B grade		
	1505 (high viscosity, unfilled)	**3235 (30% glass fiber, general purpose)**	**4235 (30% glass fiber, UL 94 V-0)**
Hot gas welding	Good	Satisfactory	Unsatisfactory
Heated tool welding	Good	Good	Unsatisfactory
Friction welding	Very good	Very good	Good
Ultrasonic welding	Very good	Very good	Very good

28.2.2 Heated Tool Welding

Bayer: Pocan

The recommended hot plate welding parameters for Pocan PBT are:

- Hot plate temperature: 280–350°C (536–662°F).
- Joining pressure: 0.1–1.0 N/mm^2 (14.5–145 psi).

Reference: *Hot Plate Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

GE Plastics: Valox (form: injection-molded plaque)

High strengths can be attained in heated tool welds of PBT specimens. Relative weld strengths in excess of 90% have been demonstrated for 3.2 mm (0.13 inch) thick specimens using heated-tool temperatures between 290 and 350°C (554–662°F), with a maximum of about 96% at a heated-tool temperature of 305°C (581°F). In the 6.1 mm (0.24 inch) thick material, higher relative weld strengths, of about 99%, have been demonstrated for heated-tool temperatures in the range 305–365°C (581–689°F). The thickness of the parts does have a small effect; with increasing part thickness, the optimum temperature process window appears to shift to higher temperatures. A higher weld penetration appears to result in higher weld strength. An increase in the heating time appears to reduce the heated-tool temperature required for obtaining high weld strengths.

In 30% glass-filled materials, relative weld strengths of about 50% can be obtained in the 3 mm (0.12 inch) thick specimens over a wide range of temperatures 230–380°C (446–716°F). In the 6.1 mm (0.24 inch) thick material, the relative strengths are consistently higher than for the thinner specimens; a maximum weld strength of about 55% has been demonstrated. However, because the thinner specimens have a higher tensile strength, higher absolute strengths can be attained in the thinner specimens.

Repeatability studies showed that high average weld strengths could be achieved in 6.1 mm (0.24 inch) thick specimens; the highest average weld strengths obtained were 58.8 MPa (8529 psi) for a heated-tool temperature of 350°C (662°F) and 58.5 MPa (8485 psi) for a heated-tool temperature of 335°C (635°F), with the standard deviations being less than 5%. While heated tool welding can produce strong welds, it requires careful dimensional and temperature control, and continuous cleaning of the heated-tool surface.

Reference: Stokes VK: A phenomenological study of the hot-tool welding of thermoplastics Part 2. Unfilled and glass-filled poly(butylene terephthalate). *Polymer*, 41(11), p. 4317, 2000.

GE Plastics: Valox 325 (form: extruded sheet)

Test specimens were cut from 3.0 mm (0.12 inch), 5.8 mm (0.23 inch), and 12.0 mm (0.47 inch) thick extruded sheet. Welds were made using melt and weld penetrations of 0.13 mm (0.005 inches) and 0.66 mm (0.026 inches), respectively, hot plate temperatures between 305 and 320°C (581 and 608°F), and a seal time of 10 seconds.

The weld zones were nonuniform; the thickness increased from the center to the edges.

Reference: Stokes VK: Comparison of the morphologies of hot-tool and vibration welds of thermoplastics. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

GE Plastics: Valox 325 (form: pipe)

High strengths can be attained in heated tool welds between very dissimilar materials. In heated tool welds of polycarbonate to the semicrystalline polyester PBT, weld strengths equal to that of PBT are obtainable. The use of different heated-tool temperatures is important for obtaining high strengths in welds between dissimilar materials. The heated-tool temperatures varied from 232 to 316°C (450–600°F) for polycarbonate and from 246 to 316°C (475–600°F) for PBT. In addition to the heated-tool temperatures, the weld strength also depends on the melt time. The highest weld strengths were attained at the longer melt time of 20 seconds. The very high weld strengths obtained for heated tool welding are consistent with those obtained in vibration welds of these two materials.

In heated tool welds of polyetherimide to the semicrystalline polyester PBT, weld strengths equal to 90% of the strength of PBT are obtainable. The heated-tool temperatures varied from 371 to 427°C (700–800°F) for polyetherimide and from 260 to 302°C (500–575°F) for PBT. In addition to the heated-tool temperatures, the weld strength also depends on the melt time.

Reference: Stokes VK: Experiments on the hot tool welding of dissimilar thermoplastics. ANTEC 1993, Conference proceedings, Society of Plastics Engineers, New Orleans, May 1993.

Hoechst Celanese: Celanex

Thermal fusion welding is now suitable for joining parts ranging from some of the smallest to the largest moldings produced using the typical welding conditions given in Table 28.7. All grades of Celanex resins are suitable for bonding by this technique and strengths of 70–100% of the resin strength can be expected with unfilled grades. Due to the limited mixing of glass fibers across the joint, the weld strength of reinforced grades generally will not exceed that of the base resin.

The importance of rapid movement cannot be overemphasized. Celanex resin is a rapidly crystallizing material with a relatively sharp melting point. Optimum weld strengths will not be obtained if the surface temperature drops below the melt point prior to contact. Because of this correlation between weld strength and the time between heating the platen and weld contact, care should be taken to ensure that the distances moved and times required are as short as possible. The holding pressure should be adjusted to maintain the parts in secure contact without causing an excessive amount of the molten resin to flow. Excessive pressure could displace the molten material, and cause unmelted resin to remain in contact, resulting in poor adhesion across the joint as well as in the generation of heavy flash.

Under optimum conditions, about two-thirds of the molten resin should flow from the joint, that is, 0.25 mm (0.010 inches) when plasticized to a 0.38 mm (0.015 inch) depth. This will provide a suitable layer of melt to form a bond. A holding pressure of 15–35 psi (0.1–0.24 MPa) on the joint area has been found generally satisfactory.

Reference: *Celanex Thermoplastic Polyester Properties and Processing (CX-1A)*, Supplier design guide (HCER 91-343/10M/692), Hoechst Celanese Corporation, 1992.

28.2.3 Ultrasonic Welding

Bayer: Pocan

At a frequency of 20 kHz, an amplitude of 30–50 μm is recommended for ultrasonic welding of Pocan PBT.

Table 28.7. Typical Hot Tool Welding Conditions for Celanex Polyester PBT

Platen (Hot Plate) Temperature, °F (°C)	Heat Time (s)	Cool Time (s)
540–640 (282–338)	12–30	6–12

Reference: *Ultrasonic Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

Hoechst Celanese: Celanex

Celanex can be successfully joined to itself via ultrasonics. Of the common ultrasonic joints available, the scarf joint is preferred for Celanex. Energy directors, such as those developed for amorphous plastics, are not suitable for the welding of crystalline materials, and are not recommended.

Other joint designs suitable for Celanex are the shear bead and the interference joint. Shear beads do not usually offer high strength; however, they are very satisfactory where hermeticity is the basic requirement. Tests run on 19.1 mm (0.75 inches) diameter containers assembled to lids by shear-bead joints showed that welds withstood an internal pressure of 100 psi (0.69 MPa).

Interference joints are used successfully in applications where a slight warpage is present, which would prevent full contact of a scarf joint.

Basic welding parameters are as follows:

- Material should be clean and free of any type of mold spray.
- Drying of the parts prior to welding is not necessary because of the low water absorption of Celanex.
- Amplitudes in the range of 0.002–0.006 inches (0.05–0.15 mm) may be used, although 0.004–0.006 inches (0.1–0.15 mm) are preferred. These are easily attainable with simple booster horns.
- Pressures of 20–40 psi (0.14–0.28 MPa) are generally satisfactory. It is a sound practice to use the lowest pressure that gives a satisfactory joint.
- Weld times for Celanex are normally less than one second. Hold time (the time required for solidification after the sonics have been turned off) is normally very short, in the order of 0.1–0.2 seconds, because of the quick set of the material.

Parameters selected by the aforementioned criteria will usually give sound and strong joints. It should be recognized that the joint is not glass-reinforced, and therefore the ultimate joint strength in the case of glass-reinforced Celanex is the tensile strength of unfilled Celanex.

Reference: *Celanex Thermoplastic Polyester Properties and Processing (CX-1A)*, Supplier design guide (HCER 91-343/10M/692), Hoechst Celanese Corporation, 1992.

PBT

In ultrasonic welding, it was found that irrespective of the amplitude, optimum energy conversion takes place at an optimum welding force of between 300 and 500 N (67–112 lbf). This optimum welding force permits the fastest possible conversion of energy. Maximum ultimate breaking forces are only achieved in the area of optimum welding force, and these cannot be increased any further after an optimum welding time.

The generator energy and thus the change in damping are not in themselves process parameters that can be used to monitor the weld-seam quality. In order to reliably monitor the quality of the weld-seam strength during the welding process, it is necessary to control the welding force, the welding time, and the amplitude and/or displacement.

Welding time, welding force, and amplitude alter the structure of semicrystalline PBT. Because of the low melt temperature of the surrounding material, short welding times result in high cooling rates, thus producing an amorphous structure. Longer welding times and low cooling rates produce semicrystalline structures. Higher welding forces create a higher shear in the material during the flow motion, which produces an orientation perpendicular to the direction of load, and results in lower strength characteristics. This becomes visible in the sheared spherulites. The most homogeneous structure can be obtained with a low force and high welding time.

Reference: Netze C, Michaeli W: Correlation of welding parameters, energy conversion and mechanical weld seam properties for ultrasonic welding. ANTEC 1991, Conference proceedings, Society of Plastics Engineers, Montreal, May 1991.

GE Plastics: Valox 325 (features: general purpose grade, unfilled; process type: injection molding); **Valox 420** (material composition: 30% glass-fiber reinforcement; process type: injection molding)

Several joint designs can be utilized for ultrasonic welding Valox resins. Each design has advantages and disadvantages which must be taken into consideration in relation to the requirements of the finished part.

The scarf joint was developed specifically for use on engineering thermoplastics such as Valox PBT resins. This joint provides excellent welds because the frictional heat generated produces an even melt of the plastic over the entire face of the weld area. It does not require the melted resin to flow from one area to another.

When welding Valox glass-reinforced resins, the strength obtained will only be equal to the strength of the unfilled Valox resin, because no fiber interflow occurs across the face of the joint during welding. However, it is possible to obtain 100% strength of the base resin with little sacrifice in weld time or other conditions. Hermetic seals are obtainable on circular parts two inches (50 mm) or less in diameter.

The scarf joint can also be easily molded into parts, although the joint does require that the angles of the two parts be equal to within 1–1.5°. A tolerance of ± 0.25 mm (0.01 inches), within most part tolerances, is acceptable for achieving good weldability.

Advantages:

- Scarf joint can be easily molded into most parts.
- High strengths can be obtained.
- Hermetic seals can be obtained.
- Little sacrifice in welding time.
- Good welds obtainable with liberal tolerances.

Disadvantages:

- Part/joint design must be circular or oval in shape.

Results of ultrasonic welding trials on a sealed container using the scarf joint design are given in Table 28.8.

The shear joint will produce welds with strengths equal to 100% of the tensile strength of the Valox base resin. Hermetic seals can be produced with this joint in parts having square corners or rectangular designs, but weld times in the range of two to three times that of other designs are required as larger amounts of resin are being melted. Substantial amounts of flash will also be visible on the upper surface after welding.

Advantages:

- Hermetic seals can be obtained.
- High weld strengths.

Disadvantages:

- Long weld times required.
- Flash visible at joint area.

Bead shear joints, when compared to shear joints, offer faster weld times with flash usually hidden. Rectangular or sharp cornered parts molded from Valox resins can be hermetically sealed. However, the design produces lower strength welds, and should not be utilized where high strength is required.

Table 28.8. Ultrasonic Welding of a Sealed Container Using a Scarf Joint Design and Valox 325 and Valox 420 Resins

Material (s)	Weld Time (s)	Hold Time (s)	Weld Pressure (psi)	Horn Amplitude (inches)	Scarf Joint (degrees)	Hermetic Seal	Burst Pressure (psi)
Valox 325	1.0	0.5	60	0.0032	45	Yes	600
	0.5	0.5	60	0.0032	45	Yes	500
	0.5	0.5	90	0.0032	45	Yes	500
Valox 420	1.0	0.5	60	0.002	45	Yes	1000
	0.5	0.5	60	0.002	45	Yes	800
	0.5	0.2	60	0.002	45	Yes	800
	0.5	0.2	30	0.002	45	Yes	1000
	0.5	0.5	60	0.0032	45	Yes	1000

There are several considerations in designing parts or modifying existing parts to make ultrasonic welding less critical:

- Part design should allow the horn to contact the parts as near to the weld area as possible (near field welding).
- The weld area and the point of contact with the horn should be in the same plane. If, because of design this is not possible, the joint should depart from the plane, but not the horn. Difference in planes greater than 6.2 mm (0.25 inches) is not recommended.
- Weld areas should be as symmetrical as possible.
- Wall thickness should be uniform and at least 1.5 mm (0.06 inches) thick.
- Weld areas should be no larger than 63.5 mm (2.5 inches) in diameter.
- Minimize protrusions.
- Design in stops and flash wells where possible.

Valox resins, natural or pigmented, should have similar welding characteristics. Since little, if any, difference should be experienced in changing colors or in changing from colored to natural, machine settings should vary minimally.

Glass-reinforced resin systems weld slightly better than unreinforced resins because of their higher modulus and stiffness. Strengths obtained with the glass-reinforced resins will be equal to the maximum strength obtained with unfilled resin, because little, if any, fiber intermeshing occurs.

Ultrasonic welding of Valox thermoplastic resins can be effectively carried out following these key points:

- The various grades of Valox resins, unreinforced and reinforced, natural and pigmented, can be ultrasonically welded with strength approaching the base resin.
- The scarf or shear-type joint designs are recommended for ultrasonic welding all Valox resins where applications require maximum strength.
- Common joint designs will produce acceptable welds where strength is not a major requirement. Horn amplitude range required for satisfactory welds is 0.002–0.006 inches (0.05–0.15 mm).
- Hermetic welds can be achieved on properly designed parts using scarf or shear-type joint design and a horn amplitude range of 0.002–0.006 inches (0.05–0.15 mm).

A special form of ultrasonic spot welding can be used to bond Valox resin to Valox resin. The horn tip vibrates ultrasonically and passes through the top part, entering the bottom part to a depth of one-half the top part thickness. While the molten plastic displaced is shaped by a radial cavity in the tip and forms a neat raised ring on the surface, energy is simultaneously released at the interface, producing the essential frictional heat. As penetration of the bottom part is made, displaced molten plastic flows into the preheated area and forms a permanent molecular bond. Spot welding replaces adhesives, rivets, staples, and other mechanical fasteners. Ultrasonic systems used for spot welding may be fixed or portable. Portable units are especially suited for bulky parts or hard to reach joining surfaces.

Reference: *Valox Design Guide*, Supplier design guide (VAL-50C), General Electric Company, 1986.

Bayer: Pocan B1505 (features: general purpose grade, unfilled); **Pocan B3235** (features: natural resin; material composition: 30% glass-fiber reinforcement); **Pocan B4235** (features: flame retardant; material composition: 30% glass-fiber reinforcement)

Ultrasonic welding, which has many advantages when used for structural materials, also produces short welding times and good joint strength with Pocan resin. The advantages of this process are apparent not only in actual welding but also in the embedding of metal inserts, such as threaded bosses. Essential preconditions for ultrasonic welding are an exact fit between the mating parts and the ability to accomplish the joining operation without additional mechanical pressure.

Both the energy director and mash welding technique are equally suitable for ultrasonic welded joints. Stepped joining is especially recommended, since it reduces, to a large extent, the excess material from the energy director because of the relatively narrow thermoelastic range of Pocan resin. Furthermore, stepped joining in general produces a stronger joint than butt welding, since the total area of the mating surface is larger. Regardless, the highest strength values are obtained at a relatively low welding pressure and high amplitude.

Reference: *Pocan Thermoplastic PBT Polyester—A General Reference Manual*, Supplier design guide (55-B635(7.5)J), Mobay Corporation, 1985.

28.2.4 Vibration Welding

GE Plastics: Valox 325 (form: 3.2 mm (0.13 inch) thick injection molded plaque); **Valox 310** (form: 6.1 mm (0.24 inch) thick injection-molded plaque)

Valox 325 has been shown to weld well with PC/PBT; welds with strengths of 98% of the strength of PC/PBT have been demonstrated for the following welding conditions: frequency of 120 Hz, amplitude of 3.175 mm (0.125 inches), pressure of 0.90 MPa (131 psi), weld penetration of 0.56 mm (0.022 inches) and a weld time of 1.7 seconds. However, it does not weld to M-PPO or PPO/PA.

Valox 310 welds extremely well to PEI; welds with strengths of 95% of the strength of PBT have been demonstrated for the following welding conditions: frequency of 120 Hz, amplitude of 3.175 mm (0.125 inches), pressure of 0.90 MPa (131 psi), weld penetration of 0.57–1.35 mm (0.022–0.053 inches) and a weld time of 2.7–4.4 seconds; or frequency of 400 Hz, amplitude of 0.635 mm (0.025 inches), pressure of 3.45 MPa (500 psi), weld penetration of 1.33 mm (0.052 inches) and a weld time of 4.1 seconds.

Reference: Stokes VK: The vibration welding of poly (butylene terephthalate) and a polycarbonate/poly(butylene terephthalate) blend to each other and to other resins and blends. *Journal of Adhesion Science and Technology*, 15(4), p. 499, 2001.

GE Plastics: Valox 325 (form: extruded sheet)

Test specimens were cut from 3.0 mm (0.12 inch), 5.8 mm (0.23 inch), and 12.0 mm (0.47 inch) thick extruded sheets. Welds were made at a frequency of 120 Hz, a weld amplitude of 1.59 mm (0.063 inches), a nominal penetration of 0.5 mm (0.02 inches), and weld pressures between 0.52 MPa (75 psi) and 13.79 MPa (2000 psi).

The weld zones were of nonuniform thickness, except near the edges. The weld zone thickness decreased with increasing weld pressure.

Reference: Stokes VK: Comparison of the morphologies of hot-tool and vibration welds of thermoplastics. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

GE Plastics: Valox 310 (features: 6.35 mm (0.25 inch) thick; form: injection molded plaque)

Under the right conditions, very high weld strengths can be achieved in 120 Hz cross-thickness welds of PBT. Cross-thickness welds do not necessarily attain the highest strengths at the process conditions under which normal-mode welds have high strengths. Therefore, optimum weld conditions for low frequency (120 Hz) welds must be based on cross-thickness weld data.

At a welding frequency of 120 Hz, because steady-state conditions are attained at relatively large penetrations of the order of 0.36 mm (0.014 inches), the cross-thickness weld strength continues to increase with the penetration. Although the weld strength increases with the weld amplitude (a) and weld pressure, strengths equal to that of PBT could not be achieved; the highest strength attained was about 93% of the strength of the base resin. At the higher pressure of 3.45 MPa (500 psi), the highest weld strengths were achieved at the smallest weld amplitudes. This shows that the intermittent cooling of the two a-unit wide strips during each cycle does affect weld strength. The amplitude affects the welding process in two opposite ways: on the one hand, larger amplitudes imply higher energy input rates and, therefore, higher film temperatures. On the other hand, the a-unit strips that undergo cooling during each cycle are wider for larger amplitudes, resulting in greater intermittent cooling. In PBT, the intermittent cooling has a larger effect than the energy input rate. This behavior could be a consequence of its semicrystalline nature: because of its sharp melting point, the intermittent cooling during each cycle could result in a local solidification of the material.

At the higher frequency of 250 Hz, excellent cross-thickness weld strength can be achieved in PBT, and the optimum conditions are the same as for normal-mode welds.

Reference: Stokes VK: Cross-thickness vibration welding of polycarbonate, polyetherimide, poly(butylene terephthalate) and modified polyphenylene oxide. *Polymer Engineering and Science*, 37(4), p. 715, April 1997.

GE Plastics: PBT

The achievable strengths of vibration welds of PBT to itself and other thermoplastics are given in Table 28.9.

Reference: Stokes VK: Toward a weld-strength data base for vibration welding of thermoplastics. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

GE Plastics: Valox 310 (features: 6.4 mm (0.25 inch) thick; form: injection-molded plaque)

For the conditions studied in this work, the highest strength of 120 Hz, cross-thickness vibration welds of polyester PBT was about 93% of the strength of PBT. In contrast to PC, larger amplitudes result in lower strengths of PBT welds—possibly because of more intermittent cooling of the portions of the melt exposed to the ambient. Because of the smaller weld amplitudes used, higher weld frequencies may therefore be more appropriate for PBT.

Reference: Stokes VK: The effect of fillers on the vibration welding of poly(butylene terephthalate). ANTEC 1993, Conference proceedings, Society of Plastics Engineers, New Orleans, May 1993.

Table 28.9. Achievable Strengths of Vibration Welds of Polyester PBT to Itself and Other Thermoplastics

Material Family	**PBT**			
Tensile strength[b], MPa (ksi)	65 (9.5)			
Elongation @ break[b] (%)	3.5			
Specimen thickness (mm (in.))	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)
Mating Material				
Material family[a]	ABS	PC	PBT	PEI
Tensile strength[b], MPa (ksi)	44 (6.4)	68 (9.9)	65 (9.5)	119 (17.3)
Elongation @ break[b] (%)	2.2	6	3.5	6
Specimen thickness (mm (in.))	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)
Process Parameters				
Process type	Vibration welding			
Weld frequency	120 Hz			
Welded Joint Properties				
Weld factor (weld strength/ weaker virgin material strength)	0.8	1.0	0.96	0.95
Elongation @ break[b] (%)(nominal)	1.6	1.7	3.5	4.1

[a] ABS: acrylonitrile-butadiene-styrene copolymer; PC: polycarbonate; PBT: polybutylene terephthalate polyester; PEI: polyetherimide.

[b] Strain rate of $10^{-2}s^{-1}$.

GE Plastics: Valox 310 (features: unfilled); **Valox 420** (material composition: 30% glass-fiber reinforcement); **Valox 740** (material composition: 30% mineral filler); **Valox 744** (material composition: 10% mineral filler); **Valox DR51** (material composition: 15% glass-fiber reinforcement)

The process phenomenology for the vibration welding of particulate and glass-filled PBT is clearly similar to that for neat resins: the penetration-time curves exhibit the four phases that are typical for neat resins. In all cases, with all other parameters held constant, the cycle time decreases with an increase in pressure.

For the same base resin, the filler content has a remarkably small effect on the steady-state penetration rate. Even the effect on the cycle time appears to be small for the same filler type; however, for the same filler loading, the cycle times are lower for the glass-filled materials.

For the same base resin, increasing filler content reduces the attainable relative weld strength. Although the base strengths of Valox 740 and Valox 420 are very different (52.7 MPa (7644 psi) and 90.6 MPa (13140 psi), respectively), their maximum relative weld strengths are remarkably the same, on the order of 0.6. Increase in filler content does decrease the ductility of the weld, that is, the relative strain at which failure occurs in the weld decreases.

One way of assessing the effect of fillers is to compare the maximum weld strength with that of the base resin. This is not easily done because, in addition to the main filler, filled materials may contain additives that can affect the mechanical behavior of the base resin—and this information is not available for commercial materials. In the absence of more information, the strength of straight PBT may be used as a reference. The strength of this semicrystalline resin can depend on the processing conditions and the location on the plaque from which the test specimen is cut; for Valox 310 four bars had strengths of 65.2 MPa (9456 psi), 60.1 MPa (8716 psi), 61.8 MPa (8963 psi), and 58.7 MPa (8513 psi) giving a mean strength of 61.5 MPa (8919 psi). The four filled grades, Valox 744, Valox 740, Valox DR51, and Valox 420, exhibited maximum weld strengths of 59.2 MPa (8586 psi), 32.5 MPa (4713 psi), 59.3 MPa (8600 psi), and 54.4 MPa (7890 psi), respectively. Using the strength (61.5 MPa (8919 psi)) of PBT as a measure of the strength of the base resin, the strengths of the welds of the filled materials relative to that of the base resin, are given, respectively, by 0.96, 0.53, 0.96, and 0.88.

Welds of the 30 wt% mineral-filled PBT are only able to attain about 50% of the strength of the base resin. The relative strengths of the remaining three mineral- and glass-filled grades are remarkably high in the order of 90%–95%. Even the 30 wt% glass-filled grade can attain about 90% of the strength of the base (filled) resin.

Reference: Stokes VK: The effect of fillers on the vibration welding of poly(butylene terephthalate). ANTEC 1993, Conference proceedings, Society of Plastics Engineers, New Orleans, May 1993.

28.2.5 Spin Welding

GE Plastics: Valox

The glass-reinforced grades yield a weld that may approach the original tensile strength of the base resin because they produce little intermeshing of glass fibers. For sealed containers the best results are obtained with a shear joint. This joint is self-locating and is recommended when high strength, hermetic seals are required, such as on thin-walled containers.

Reference: *Valox Design Guide*, Supplier design guide (VAL-50C), General Electric Company, 1986.

Bayer: Pocan B1505 (features: general purpose grade, unfilled); **Pocan B3235** (features: natural resin; material composition: 30% glass-fiber reinforcement); **Pocan B4235** (features: flame retardant; material composition: 30% glass-fiber reinforcement)

Friction welding is highly suitable for Pocan resin. Glass-fiber reinforced grades can also be reliably welded together using this method. It is important that the welding surfaces are of suitable design. Pressure and rotational speed are dependent on one another and can easily be determined empirically.

Reference: *Pocan Thermoplastic PBT Polyester—A General Reference Manual*, Supplier design guide (55-B635(7.5) J), Mobay Corporation, 1985.

28.2.6 Hot Gas Welding

GE Plastics: PBT

Results of this study indicated that satisfactory welds could not be achieved with polyester PBT. With hot gas welding, the contractions that occur as the welds cool cannot be countered by maintaining pressure on the weld via the surrounding material, as is the case in many other plastics welding techniques. Hence contraction cavities and incomplete fusion at the joints are likely and, if the single V butt weld is used, then notches are produced in the root. The results are that welded sheets have low ductility and reduced strength, although the strength reduction is not great if optimum welding conditions are used. Impact properties are also inferior, particularly if the impact occurs on the face of the weld. A double-V butt weld improves the impact properties considerably.

The optimum air temperature for polyester PBT was determined to be 340°C (644°F). The speed of travel of the welding gun and the pressure applied are determined by the operator who will be constantly adjusting these parameters to achieve a weld of satisfactory appearance. The appearance of the weld is a good guide to its quality: the smoothness of the profile and the nature of the wash are features deserving particular attention. The ratio of weld strength (tensile) to that of the parent material was 0.76 using a single-V butt weld and 0.97 using a double-V butt weld.

Reference: Turner BE, Atkinson JR: Repairability of plastic automobile bumpers by hot gas welding. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

28.2.7 Laser Welding

BASF: Ultradur

Suitable Ultradur combinations for laser welding are given in Table 28.10.

Table 28.10. Ultradur Product Combinations Suitable for Laser Welding

Transmitting Component	Absorbing Component
B4300G2	B4520 sw 00110
B4300G4	B4520 sw 00110
B4300G6	B4520 sw 00110
B4300G6	B4300G6 sw 15073 Q16
B4300G10	B4520 sw 00110
B4520	B4520 sw 00110
S4090G6	S4090G6 sw 15077
B4300G6 LT sw*	B4300G6 sw 15073 Q16

*Black transmitting component.

Reference: *Transmission Laser-Welding of Thermoplastics*, Technical Information (WIS 0003 e 01.2001), BASF Aktiengesellschaft, 2001.

28.2.8 Infrared Welding

BASF: Ultradur (material composition: 0.5% carbon black)

Infrared (IR) welding was shown to effectively join both natural color and black PBT. For the natural color PBT, IR heating for 29 seconds at a heating distance of 8.94 mm (0.35 inches) and a pressure of 0.88 MPa (128 psi) produced the highest joint strength of 59 MPa (8557 psi) which is 96% of the bulk strength. For black PBT, IR heating for 31.6 seconds at a heating distance of 15.34 mm (0.604 inches), 75% power level, and a pressure of 0.44 MPa (64 psi) resulted in the highest joint strength of 51.8 MPa (7513 psi) which is 85% of the bulk strength. For both materials there was an optimum heating time. For natural color PBT (and probably for black PBT) there was also an optimum pressure. For the black PBT, the surface temperature could be raised rapidly resulting in joint strengths of 70% of the bulk for heating times of 8 and 9 seconds. For longer heating times the surface temperature was too high resulting in degradation. Increasing the joint strength in the black PBT required increasing the heating distance and lowering the power which resulted in substantially longer heating times. Therefore, depending on the strength desired from the joint, adding the pigment may help or hinder the cycle time.

In summary, IR welding of PBT was very successful with welding of black PBT with respectable joint strength being possible with heating times of less than 10 seconds. This makes IR welding an excellent method to consider for joining high temperature polymers.

Reference: Chen YS, Benatar A: Infrared welding of polybutylene terephthalate. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

28.2.9 Induction Welding

GE Plastics: Valox 325 (form: injection-molded plaque)

A commercial high-frequency generator (Emabond Systems HD500) was used for making the induction welds. Pressure applied by an air cylinder was used to control the weld interface pressure; two weld pressures of 0.21 MPa (30 psi) and 0.41 MPa (60 psi) were used.

Relative weld strengths as high as 43% were demonstrated, although it should be remembered that, while this study focused on the tensile strengths of welds, in induction welding, the weld joints are mainly subjected to shear stresses.

Reference: Stokes VK: Experiments on the induction welding of thermoplastics. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

28.2.10 Solvent Welding

Huls AG: Vestodur

The good solvent resistance of PBT precludes the use of most solvents for joining Vestodur parts.

Reference: *Huls Vestodur Polybutylene Terephthalate*, Supplier technical report (42.01.003e/505.93/bu)—Huls Aktiengesellschaft, 1993.

BASF AG: Ultradur

Two solvents that can be used for welding PBT are hexafluoroacetone sesquihydrate and hexafluoro-2-propanol. However, both are skin and eye irritants, and the necessary safety precautions must be observed in handling them, that is, the use of fume cupboards, safety goggles, and barrier creams.

Reference: *Ultradur Polybutylene Terephthalate (PBT) Product Line, Properties, Processing*, Supplier design guide (B 575/1e—(819) 4.91), BASF Aktiengesellschaft, 1991.

Hoechst AG: Celanex

Because of Celanex's good solvent resistance, solvent bonding is not recommended.

Reference: *Celanex Polybutylene Terephthalate (PBT)*, Supplier design guide (BYKR 123 E 9070/014), Hoechst AG, 1990.

28.2.11 Adhesive Bonding

PBT (reinforcement: 30% glass fiber)

A study was performed on the effect of vacuum plasma pretreatment with respect to adhesive bond strength on PBT (with 30% glass-fiber reinforcement). Two types of high-strength epoxy adhesives were used: Eccobond® 2332 (a single-component adhesive) and Eccobond® 45W1 (a two-component adhesive). Eccobond® 2332 was cured for 1 hour at 120°C (248°F), Eccobond® 45W1 was used in a 1:1 ratio with Catalyst 15 and was cured for 24 hours at room temperature. The plasma-treated samples were glued together within one day of the plasma treatment.

Results showed that the bond strength of plasma pretreated samples was three times the value of nonplasma-treated samples.

Reference: Lippens P: Vacuum plasma pre-treatment enhances adhesive bonding of plastics in an environmentally friendly and cost effective way. Joining Plastics 2006, Conference proceedings, London, UK, April 2006.

GE Plastics: Valox

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 28.11 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 28.11 so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively

Table 28.11. Shear Strengths of Valox PBT to PBT Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[b]

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin grade 325	4 rms	100 (0.7)	250 (1.7)	>3150[a] (>21.9)[a]	250 (1.7)	100 (0.7)	200 (1.4)
Grade 325 roughened	60 rms	500 (3.5)	950 (6.6)	1450 (10.0)	2150 (14.8)	200 (1.4)	600 (4.1)
Grade DR51	15% glass-reinforced	100 (0.7)	400 (2.8)	4200 (29.0)	450 (3.1)	100 (0.7)	200 (1.4)
Grade 420	30% glass-reinforced	200 (1.4)	300 (2.1)	>4150[a] (>28.6)[a]	550 (3.8)	150 (1.0)	600 (4.1)
Grade 508	30% glass reinforced alloy	450 (3.1)	2100 (14.5)	3350 (23.1)	1800 (12.4)	1650 (11.4)	1250 (8.6)
Grade 732E	30% glass/mineral reinforced	950 (6.6)	>2650[a] (>18.3)[a]	>2900[a] (>20.0)[a]	>2200[a] (>15.2)[a]	950 (6.6)	1750 (12.1)
Grade 735	40% glass/mineral reinforced	900 (6.2)	>2600[a] (>17.9)[a]	>2800[a] (>19.3)[a]	>2650[a] (>18.3)[a]	350 (2.4)	750 (5.2)
Grade 830	30% glass reinforced alloy	150 (1.0)	600 (4.1)	>4050[a] (>27.9)[a]	350 (2.4)	150 (1.0)	550 (3.8)
Grade 850	15% glass reinforced alloy	200 (1.4)	400 (2.8)	>4400[a] (>30.3)[a]	1100 (7.6)	150 (1.0)	700 (4.8)

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (parentheses).

bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 instant adhesive, used in conjunction with Prism Primer 770, achieved the highest bond strengths on all grades of PBT that were evaluated. Typically, Prism 401 and Super Bonder 414 instant adhesives, Loctite 3030 adhesive, Hysol E-214HP epoxy adhesive, Hysol U-05FL urethane adhesive, and Hysol 3631 hot-melt adhesive achieved the highest bond strengths, followed by Speedbonder H4500 structural adhesive, Hysol E-00CL, E-90FL and E-30CL epoxy adhesives, and Fixmaster high-performance epoxy and rapid rubber repair. Black Max 380, a rubber toughened cyanoacrylate adhesive, and Depend 330, a two-part no-mix acrylic adhesive, achieved the lowest bond strengths on PBT.

Surface Treatments: Surface roughening, plasma treatment, UV-ozone treatment, and the use of Loctite Prism Primer 770 or 7701 have all proven to cause large, statistically significant increases in the bondability of PBT.

Other Information: Good solvents for PBT are hexafluoroisopropanol, trifluoroacetic acid, o-chlorophenol, and mixtures of phenol with chlorinated aliphatic hydrocarbons. PBT is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

Degussa AG: Vestodur

Vestodur can be bonded using commercially available adhesives based on:

- Epoxide: one- or two-pack adhesives (gap filling), suitable for larger adherent surfaces. Often works best at higher temperatures.
- Polyurethane: one- or two-pack and (reactive) hot-melt adhesives (gap filling, flexible adhesives, mostly with longer pot life and clamping time), suitable for larger adherent surfaces.
- Cyanoacrylates: one-pack adhesives (short setting time), suitable for small glue-lines and adherent surfaces.

Improvement to bonding strength can be obtained by a pretreatment of the surface to be bonded, for example, by the use of primers, flame treatment, and electrical discharge.

Reference: *Vestodur Handling and Processing*, Supplier technical report (01/te/1000e), Degussa AG.

Hoechst Celanese: Celanex

Parts molded of Celanex resin can be bonded to each other or to dissimilar materials using commercially available adhesives. The most commonly employed adhesives for Celanex resin are those based on epoxy resin, polyurethanes or cyanoacrylates. Adhesive manufacturers tailor their formulations to conform to a wide range of performance standards. When selecting an adhesive, attention must be given not only to mechanical performance, but also to the chemical environment and the operating temperatures to which the assembly will be exposed.

Best bond strengths are obtained on parts made of Celanex when the mating surfaces have been sanded and degreased by wiping with a solvent. Although high viscosity adhesives are sometimes used as gap-fillers, good bonds normally require closely mated surfaces.

One group of adhesives that may be used with Celanex resins are those based on cyanoacrylate monomers. Tensile shear strengths of 400–450 psi (2.8–3.1 MPa) can be obtained with these adhesives. They are recommended for environments involving contact with alcohol, benzene, acetone, gasoline, propane, light oil, or similar solvents. Alkaline materials and dilute acids may reduce bond strength. Eastman 910 softens at 165°C (330°F) and Permabond softens at 140°C (284°F). A curing time of 24 hours at room temperature is recommended before use.

Another group of adhesives that works well with Celanex are epoxy-based. Suggested epoxy adhesives are Scotch-Weld 2214 and 2216, manufactured by the 3M Co., St. Paul, Minn. Scotch-Weld 2214 is a one-part epoxy which can be cured in 40 minutes at 121°C (250°F). Scotch-Weld 2216 is a two-part system which cures in 24 hours at room temperature. Both of these adhesives give tensile shear strengths in excess of 500 psi (3.4 MPa), and are resistant to such environments as fuels, salt spray and air up to 93°C (200°F) continuous, and 121°C–149°C (250°F–300°F) short term.

Reference: *Celanex Thermoplastic Polyester Properties and Processing (CX-1A)*, Supplier design guide (HCER 91-343/10M/692), Hoechst Celanese Corporation, 1992.

BASF AG: Ultradur

The adhesives recommended for bonding Ultradur parts together, or to articles made of other materials are the two-component types, for example, epoxy, polyurethane, silicone, and cyanoacrylate. Bonds of utmost strength can be attained by roughening the surfaces to be bonded beforehand and degreasing them with a solvent, for example, acetone.

Reference: *Ultradur Polybutylene Terephthalate (PBT) Product Line, Properties, Processing*, Supplier design guide (B 575/1e—(819) 4.91), BASF Aktiengesellschaft, 1991.

Hoechst AG: Celanex

For bonding Celanex, two-pack adhesives based on epoxy resins, polyurethanes or silicone resins are recommended. Depending on the application, cyanoacrylate or hot-melt adhesives may also be used.

Reference: *Celanex Polybutylene Terephthalate (PBT)*, Supplier design guide (BYKR 123 E 9070/014), Hoechst AG, 1990.

GE Plastics: Valox

Parts molded from Valox thermoplastic polyester can be bonded to one another, as well as to dissimilar materials using commercially available adhesives (Table 28.12). Since adhesive bonding involves the application of adhesive media between two molded parts, end-use environment is of major importance in selecting an adhesive system.

Operating temperatures, bond appearance, joint design, and tensile and flexural properties must be taken into consideration. Bonding procedures are: light sanding, followed by wiping with a degreasing solvent, application of adhesive, and slight clamping pressure.

The adhesives listed here have demonstrated satisfactory bond strengths with laboratory specimens. There are several factors to consider when selecting an adhesive. These include the effect of the adhesive on the substrate, that is, bond strength, compatibility, and the properties the adhesive would have to exhibit in the end-use environment. In most cases, more than one adhesive could fulfill the requirements of an application. Therefore, it is suggested that the adhesive selected be tested under the actual end use conditions to determine its suitability.

Reference: *Valox Design Guide*, Supplier design guide (VAL-50C), General Electric Company, 1986.

28.2.12 Mechanical Fastening

DuPont: Crastin GR

Snap-fits: The suggested allowable strains for lug type snap-fits are given in Table 28.13.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I*, Supplier design guide—DuPont Company, 2002.

Hoechst Celanese: Celanex

Snap-fit Assemblies: Snap-fit assemblies are possible with Celanex fiberglass reinforced resins but, due to the rigidity of the material, the allowable interference between the mating parts during assembly is limited. The unreinforced grades, Celanex 2000, 2002, and 2012 are best adaptable to snap-fit assemblies requiring the most interferencez.

The elements to be joined must be designed to permit deflection during assembly without exceeding the elastic limit of the material. In a snap-fit design,

Table 28.12. Recommended Adhesives for Use with Valox Polyester PBT Resins

Adhesive	Classification	Valox	Foamed Valox	Manufacturer
Scotch-Weld 2216 B/A	Epoxy—two-part	x	x	3M Company
Scotch-Weld 2214 regular	Epoxy—one-part	x	x	
Scotch Weld 2214 hi-dens.	Epoxy—one-part	x	x	
Scotch-Weld 3532 B/A	Urethane—two-part	x	x	
Scotch-Weld 3520 B/A	Epoxy—two-part	x	x	
Scotch-Grip 4693	Elastomer—one-part		x	
Tycel 7002/7250	Urethane—two-part		x	Lord Corporation
Tyrite 7500A/7510C	Urethane—two-part		x	
Versilok 506 Accelerator 4	Acrylic—two-part	x	x	
Versilok 510 Accelerator 4	Acrylic—two-part		x	
Superbonder 414, 420, 422, 430, 495	Cyanoacrylate—one-part	x	x	Loctite Corporation
Black Max	Cyanoacrylate—one-part	x	x	
Oatey Pipe Cement	Solvent-based—one-part		x	Oatey Company
EPON 828 V-40, V25	Epoxy—two-part	x	x	Miller-Stephenson Chemical
34N/62MT	Urethane—two-part		x	Synthetic Surfaces

Table 28.13. Suggested Allowable Strains for Lug-type Snap-fits in Crastin GR

Material	Allowable Strain (%)	
	Used Once (New Material)	Used Frequently
Crastin GR	1.2	0.6

generous radii should be provided to ease the assembly of the two mating elements and dimensions on the mating parts should be selected such that no continuing stress is exerted after the parts are assembled.

When Celanex resins are molded, they solidify and become hard in the mold very rapidly. Consequently, there is little opportunity for satisfactory stripping of undercuts in the mold. In most cases, those design elements which constitute undercuts in the mold would need to be machined in a post-molding operation.

Tapping and Self-tapping Screws: Threads may be cut in Celanex resin components on a lathe. Celanex resins may also be threaded with conventional taps and dies. A special tap designed for plastics, which has two flutes and a 6–8° rake, offers some advantages in greater chip clearance. Speeds should be half the surface speed recommended for drilling.

In many Celanex resin applications, mechanical assembly to other components is required. This can be done conveniently with self-tapping screws. This method of fastening requires only drilling or molding a pilot hole into the Celanex resin part. ‘Swageform B’ thread-forming screws, Type-‘BF’ thread-cutting screws, ‘Plastite’ thread-forming screws, and ‘Hi-Lo’ thread-forming (blunt point) and thread-cutting (shank slotted) screws, are excellent for mechanically fastening Celanex. Thread-forming screws give somewhat higher stripping torques and pull-out strengths.

Driving torque values indicate the torque necessary to drive the screws into the Celanex resin pilot holes. Stripping torque values indicate the tightening torques that will strip Celanex resin threads formed by the self-tapping screws. In many applications, a low driving torque with a substantial drive/strip ratio is of primary importance. Although the driving torque values obtained from Celanex resin are comparable to those necessary for fastening other thermoplastic materials, the stripping torque values for Celanex resin are considerably higher, sometimes by a factor of 2 or 3, than the values for other plastics. The higher the torque used to tighten self-tapping screws (“seating torque”), the greater the clamping force that will be exerted between the components assembled. Screw manufacturers generally recommend a seating torque that is half to three-fourths of the stripping torque.

In some other applications, the holding strength is the primary consideration. The driving and stripping torques may be of minor importance, although the drive torque must not be excessive, and the drive/strip ratio must be reasonable (about 3:1). The holding strength is measured by pull-out force (the force necessary to pull out, without turning, the self-tapping screws from the Celanex resin parts).

In still other applications, loosening from vibration is important. Independent laboratory testing has shown that Celanex resin assemblies joined with self-tapping screws have excellent resistance to vibration by the military standard used for ground vehicles.

Molded-in Inserts: Metal inserts may be molded into Celanex resins with good results. Inserts of steel, brass, and aluminum were evaluated and found to be acceptable when proper guidelines were used.

The following recommendations should be followed for optimum results:

- Use an insert with a coarse knurl for maximum holding power. The knurl should end below the surface of the plastic.
- Radius all sharp corners on the insert. Sharp corners on the knurl should be broken by tumbling or grit blasting.
- Inserts should have blind internal holes as opposed to through holes, and have a generous radius or spherical shape at the closed end.
- The open end of the insert should project above the surface of the molding.
- Inserts should be at room temperature when molded.
- Wall thickness of the Celanex around the insert should be no less than half the insert OD.

Molded-in Threads: Standard systems (Unified, Acme, etc.) can be utilized when designing threads for Celanex resins. However, because of the lower shear strength of this material as compared with metals, less torque is required to strip a plastic thread in any given design. On the other hand, most metal threads are greatly over-designed and the exceptionally high stripping torques obtained are far above the actual performance requirements. Thus, using proper thread designs, Celanex resin components can be designed with the high stripping torques demanded for many applications.

Internal and external threads can be fabricated in Celanex resin parts either by molding or machining in a post-molding operation. This material can be readily machined with standard metal-working tools, and this procedure is generally recommended for threads below 0.25 inches (6.4 mm) diameter. Cored holes that are to be machine-tapped after molding should be provided with a chamfer starting from a shallow counterbore. This will prevent the chipping of the edge of the hole during the tapping operation.

Larger internal threads may be formed by a threaded core pin, which is unscrewed either manually or automatically. External threads may be formed in the mold by splitting the thread along its axis, or by unscrewing the part from the mold. When a parting line or the slightest flash on the threads cannot be tolerated, the second method (unscrewing the part from the mold) must be used. Mold designs with automatic unscrewing operations are feasible.

Coarse threads can be molded easier than fine threads, and are therefore preferable. Threads finer than 28 pitch or closer than Class 2 should not be specified. The roots and crests of all type threads should be rounded with a 0.005–0.010 inch (0.127–0.254 mm) radius to reduce stress concentration and provide increased strength. Chamfers are also recommended.

Threaded Inserts: Ultrasonic insertion of metal inserts into drilled or molded pilot holes is feasible with Celanex resins. Insertion generally takes higher horn pressures than welding. Depending on part thickness, insert size, etc., pressures may range from 20–50 psi (0.14–0.35 MPa).

Amplitudes, on the other hand, should be kept low. Normally 0.001–0.002 inches (0.025–0.05 mm) will be satisfactory. Insertion times generally range from 0.5 to 2 seconds, depending on the insert size, while hold times range from 0.2–0.4 seconds. Typical strength values for internally threaded inserts in Celanex resin are shown in Table 28.14.

Reference: *Celanex Thermoplastic Polyester Properties and Processing (CX-1A)*, Supplier design guide (HCER 91-343/10M/692), Hoechst Celanese Corporation, 1992.

BASF AG: Ultradur

Ultradur's toughness and other mechanical properties permit self-tapping screws to be used for bonding. No problems are involved in bolting or riveting the moldings together or to articles made of other materials. By virtue of its excellent flexibility and strength, Ultradur lends itself readily to high-strength snap- and press-fit connections.

Table 28.14. Typical Strength Values for Internally Threaded Ultrasonic Inserts in Celanex Polyester PBT Resin

Insert Thread Size	Pull Out Strength, lbs (kg)	Stripping Torque, in. lbs (Nm)
8–32	100–150 (45.4–68.1)	35 (4)
1/4–20	500–700 (227–318)	80–100 (9–11.3)

Reference: *Ultradur Polybutylene Terephthalate (PBT) Product Line, Properties, Processing*, Supplier design guide (B 575/1e—(819) 4.91), BASF Aktiengesellschaft, 1991.

Hoechst AG: Celanex

Celanex moldings can be joined to each other, or to articles made from different materials by conventional methods such as riveting, flanging, or tamping or by using metal threaded inserts designed for ultrasonic or heat installation in the plastic. Mechanical assembly with screwed, snap-fit or press-fit joints is also an option, and offers the advantage of detachable joints in some cases. Assembly with spring clamps is also possible.

Reference: *Celanex Polybutylene Terephthalate (PBT),* Supplier design guide (BYKR 123 E 9070/014), Hoechst AG, 1990.

GE Plastics: Valox 310-SEO (features: flame retardant, unfilled; process type: injection molding); Valox 325 (features: general purpose grade, unfilled; process type: injection molding); Valox 420 (material composition: 30% glass-fiber reinforcement; process type: injection molding); Valox 420-SEO (material composition: 30% glass-fiber reinforcement); Valox DR-48 (features: flame retardant; material composition: 17% glass-fiber reinforcement; process type: injection molding); Valox DR-51 (material composition: 15% glass-fiber reinforcement; process type: injection molding)

Snap-fit Assemblies: A simple, economical, and rapid assembly method, snap-fitting allows Valox resin parts to be assembled to metals or plastics by engaging a molded undercut to a mating lip located on the retaining piece.

The equations for stress and deflection should be used to determine assembly force and required stiffness. The maximum fiber strain level for any particular application can be selected on the basis of acceptable permanent deformation for the application. The limits for Valox resins are: Valox 420, Valox 420-SEO—2%; Valox DR-51, Valox DR-48—2.5%; Valox 325, Valox 310-SEO—6%. If repeated assembly is anticipated, the strain level should be decreased by 1%. This can be done by increasing the beam's length, by reducing the thickness, or by tapering the thickness. These changes will affect the efforts required for assembly, and should be rechecked if critical.

Press-fit Assembles: Press-fits provide a fast, clean, and economical method of component assembly. Because the strength of the fit is dependent on a mechanical interface, the designer can assemble metals or other polymers to Valox resin (Fig. 28.1). However, since no physical bonding is involved, hermetic seals should not be expected.

In applications where the long-term holding power of an assembly is of prime importance, reliability will depend on the creep behavior of the materials used. Because of its outstanding creep resistance, Valox resin offers excellent performance in press-fit operations.

At elevated temperatures, the strength of the assembly will be altered due to changes in the effective interface caused by thermal expansion and the modulus of elasticity. The use temperature modulus can be substituted into the proper interference calculation to determine the reduced design stress. Because long-term strength is also a consideration, the apparent modulus from creep curves of Valox resin must be considered. To retain joint strength, knurls or some type of upset in the harder material are commonly used, allowing the softer material to flow into the recesses as the material relaxes.

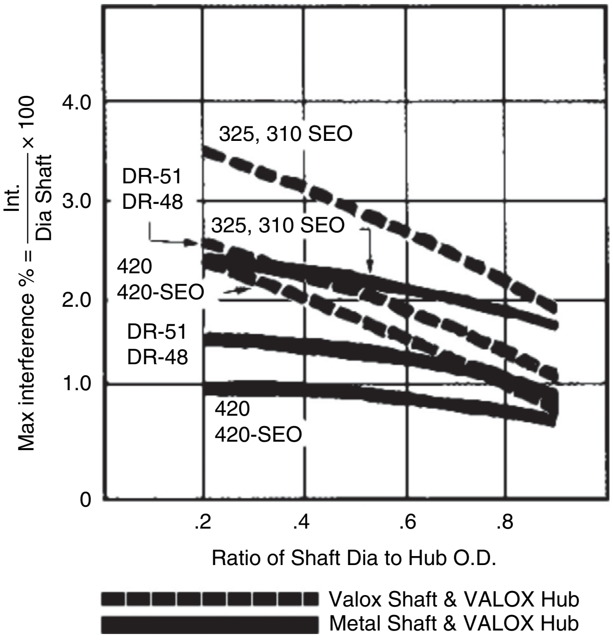


Figure 28.1. Maximum diametral interference for Valox polyester PBT and metal press fits.

Staking: For Valox resins, heat staking head temperatures of 218–289°C (424–552°F) have been used, depending upon size and number of positions being staked. Hardened polished up-setting heads, electrically heated, and temperature controlled are recommended. A slow approach should be used when heat staking to develop even melting.

Tapping and Self-tapping Screws: The use of self-tapping screws to assemble parts made from Valox resin can result in substantial savings by the elimination of molded-in threads and reduced assembly costs. It is recommended that the relationship between boss diameter and screw diameter be two to one. Bosses with a thin section will result in a reduction of stripping torque or cracking due to stresses caused by screw insertion.

Since the stripping torque increases with engagement length, for optimum results, it is suggested that the engagement length be approximately 2.5 times the diameter of the screw. The pilot hole should be slightly deeper than the length of the fastener to prevent excessive loading of the threads.

Molded-in Inserts: Valox resins perform satisfactorily with molded-in inserts. In order to minimize the stresses created at the metal-plastic interface by the difference in thermal expansion, observe the following precautions:

- Design permitting, use plain smooth inserts.
- Use simple pull-out and torque retention grooves when high torque and pull-out retention are required.
- If a knurled insert is used, keep the size of knurls to a minimum; remove all sharp corners; round the hidden end of the insert; and keep the knurl section away from part edges.
- Remove all incompatible chemicals, such as oil, from the insert.
- Employ high mold temperatures 82–104°C (180–219°F) to reduce thermal stresses.
- Provide sufficient material around the insert.

Prototyping is recommended to determine suitability for chemical, high temperature, and thermal cycling environments.

Many molded-in inserts require hermetic sealing. In such applications, there are two approaches that can be utilized to ensure hermetic seals. One such method is to coat the metal inserts with a flexible medium such as an RTV rubber, urethane, or modified epoxy systems. The coating should be applied preferably in an under-cut region which is over-molded with the Valox resin.

A second method of sealing molded-in inserts is to design in an annular space or reservoir at one end of the insert. A sealing medium such as RTV, urethane, or epoxy sealant would then be dispensed in the area to effectively create a hermetic seal.

Flexible sealants are preferred to compensate for the differences in thermal coefficient of expansion between metal and plastics.

The recommended minimum material thickness around inserts is given in Table 28.15.

Threaded Inserts: Ultrasonic insertion is a fast and economical method of installing metal inserts into parts molded of Valox thermoplastic polyester. A slow horn approach, allowing the horn to develop a homogeneous melt phase, is preferable to "pressing" the insertion.

Care must be exercised in selecting post-molding inserts to obtain satisfactory performance in various applications. Various inserts are designed for maximum pull-out strengths, torque retention, or some combination of both. Horizontal protrusion, grooves or indents are used for high pull-out strengths. Vertical grooves or knurls are used for high torque retention.

Reference: *Valox Design Guide*, Supplier design guide (VAL-50C), General Electric Company, 1986.

28.3 Liquid Crystal Polymers

28.3.1 Heated Tool Welding

Ticona: Vectra

Hot plate welding is not recommended for Vectra LCPs due to the tendency for the material to bond onto the hot plate. The strength of the weld is between 12 and 15% of the material strength.

Reference: *Vectra Liquid Crystal Polymer (LCP)*, Supplier design guide, Ticona, 2001.

Table 28.15. Recommended Minimum Material Thickness Around Molded-in Inserts in Valox PBT Resins

Material	
Aluminum	0.8 × outer radius of the insert
Brass	0.9 × outer radius of the insert
Steel	Equal to the outer radius of the insert

28.3.2 Ultrasonic Welding

Ticona: Vectra

The most important aspect of welding Vectra LCPs is that a shear joint be used. During ultrasonic welding with Vectra LCPs, the joint strength depends largely on the shear length—a longer shear length yields higher strength. Other types of joint designs, such as energy director, scarf- and butt-joints, result in low strengths. The shear joint should be designed in a conventional manner for a high modulus material, that is with about a 0.2–0.4 mm (0.008–0.016 inch) interference and a greater than 2 mm (0.08 inch) depth. The strength of the welded joint will be determined more by the depth of the joint than by the interference.

For most welding applications, a 20 kHz machine should be adequate. For very small parts, less than 13–19 mm (0.51–0.74 inches) diameter, a 40 kHz machine should be considered. Horn amplitudes will be large, generally between 0.05 mm (0.002 inches) and 0.08 mm (0.003 inches) for a 20 kHz frequency and about half that for a 40 kHz frequency machine.

The expected weld strength will depend on both the actual welding conditions and the grade of Vectra LCP being used. Joint shear strength of about 30–50% of the bulk material strength should be expected when the aforementioned guidelines are followed.

During ultrasonic welding tests, sonotrode wear was observed, which could be avoided by using a hard metal material or a polyethylene layer as a buffer. Due to the stiffness of Vectra LCPs, the ultrasonic welding process can be noisy. A silicon rubber layer underneath the parts helps to diminish the noise.

Reference: *Vectra Liquid Crystal Polymer (LCP)*, Supplier design guide, Ticona, 2001.

Hoechst AG: Vectra

Moldings made from Vectra can be joined by ultrasonic methods such as welding, riveting, flanging, staking and insertion. Shear joint welds are the most suitable design. Near-field placement of the weld area is an advantage. Vectra can be welded with the usual ultrasonic welding machines (20, preferably 40 kHz).

Choice of welding conditions (amplitude, welding time, welding pressure, etc.) depends on the Vectra grade and joint geometry. The conditions must be optimized in each case by carrying out practical trials.

Particular attention must be devoted to the production of high-quality parts for welding and to suitable joint design. The alignment and joint contours must be exactly matched to the application. It is important for the ultrasonic horn to be positioned vertically above the joint area. If horn wear occurs or surface marks are caused on the plastic part, these problems can be remedied by carbide-tipping the horn or using PE film interlayers.

Reference: *Vectra Polymer Materials*, Supplier design guide (B 121 BR E 9102/014), Hoechst AG, 1991.

28.3.3 Vibration Welding

Ticona: Vectra

With vibration welding, the specific polymer structure of Vectra LCPs causes either long welding times with low pressure, or short welding times with high pressure. Low welding pressure is recommended. With a low welding pressure, a strength of about 16% of the material properties can be achieved. It is not recommended to weld parallel to the flow direction.

Reference: *Vectra Liquid Crystal Polymer (LCP)*, Supplier design guide, Ticona, 2001.

28.3.4 Spin Welding

Ticona: Vectra

Joint design is critical for maximizing weld-line strength. With optimum design (Fig. 28.2), strengths of 50% of the material properties can be achieved.

Reference: *Vectra Liquid Crystal Polymer (LCP)*, Supplier design guide, Ticona, 2001.

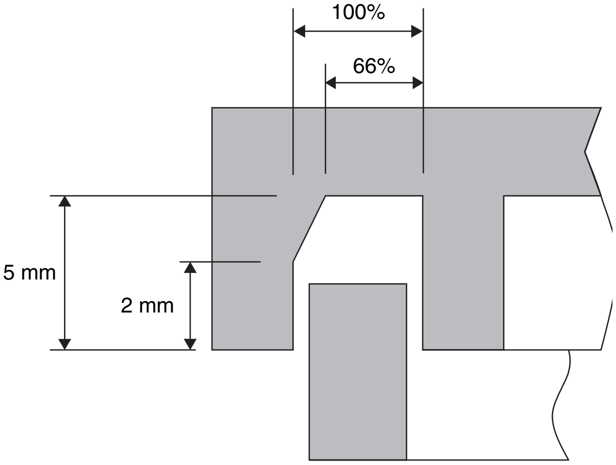


Figure 28.2. Spin welding joint design for Vectra LCP.

BASF: Ultrax 4002

Four-point bending tests on samples spin welded for 3.4 seconds were performed. Data were collected for neat LCP, 10% glass-filled LCP, 20% glass-filled LCP, and 30% glass-filled LCP. As glass fiber content increased, a significant increase in strength was observed. In nearly all cases, the results showed that maximum strength occurred at an optimum pressure and rotation speed which usually occurs in the intermediate region of the range tested. It could also be seen that strength typically decreased as the rotation speed exceeded 2500 rpm. This occurred as a result of increases in fiber axis orientation in the theta direction at high rotation speeds. The addition of glass fibers to liquid crystalline polymers (LCPs) appears to be a viable means of improving weld strength.

Reference: Festa D, Cakmak M: Influence of glass fibers on the spin welding of thermotropic liquid crystalline polymer. ANTEC 1993, Conference proceedings, Society of Plastics Engineers, New Orleans, May 1993.

LCP

Thermotropic LCPs exhibit low coefficients of friction in the solid state, high melting temperatures, and low melt viscosities. When the LCPs chains are oriented in the flow field, the orientational relaxation times are quite long, even at high temperatures. These characteristics make them a challenging class of materials to join using the spin welding process.

Reference: Festa D, Cakmak M: Spin welding behavior and structure development in a thermotropic liquid crystalline polymer. ANTEC 1992, Conference proceedings, Society of Plastics Engineers, Detroit, May 1992.

28.3.5 Laser Welding

DuPont: Zenite

Zenite reflects most of the laser power and therefore cannot be welded using this method.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I*, Supplier design guide, DuPont Company, 2002.

28.3.6 Induction Welding

Ticona: Vectra

Electromagnetic welding is suitable for Vectra LCPs. For efficiency reasons, the longer welding times can be compensated for by a multiple welding system.

Reference: *Vectra Liquid Crystal Polymer (LCP)*, Supplier design guide, Ticona, 2001.

28.3.7 Solvent Welding

Hoechst AG: Vectra

Vectra has a high resistance to solvents, so solvent welding is not possible.

Reference: *Vectra Polymer Materials*, Supplier design guide (B 121 BR E 9102/014), Hoechst AG, 1991.

28.3.8 Adhesive Bonding

Amoco Performance Products: Xydar

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 28.16 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually, as shown in Table 28.16 so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Table 28.16. Shear Strengths of Xydar LCP to LCP Adhesive Bonds Made using Adhesives Available from Loctite Corporation*

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
G-540	40% Glass-reinforced 58 rms	500 (3.5)	300 (2.1)	400 (2.8)	350 (2.4)	450 (3.1)	650 (4.5)
G-540 roughened	63 rms	1050 (7.2)	1100 (7.6)	1050 (7.2)	1100 (7.6)	1150 (7.9)	650 (4.5)
G-930	30% Glass-reinforced 106 rms	350 (2.4)	300 (2.1)	500 (3.5)	350 (2.4)	500 (3.5)	500 (3.5)
G-930 roughened	113 rms	1200 (8.3)	1450 (10.0)	1550 (10.7)	1250 (8.6)	900 (6.2)	500 (3.5)

*All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Hysol E-30CL, E-20HP, and E-214HP epoxy adhesives and Fixmaster high-performance epoxy all achieved good bond strength on the unfilled LCP resin. All other adhesives achieved moderate to poor bond strengths.

Surface Treatments: Surface roughening caused a large, statistically significant increase in the bond strengths achieved on LCP for all the adhesives evaluated, except Loctite 3105 and 3311 light-cure adhesives, for which surface roughening had no statistically significant effect. Although the process of surface roughening did not result in a significant increase in the surface roughness of the LCP, it removed a surface layer, which resulted in higher bond strengths. The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, resulted in no statistically significant change in the bondability of LCP.

Other Information: LCP is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

Ticona: Vectra

Parts made from Vectra LCPs can be effectively bonded using readily available commercial adhesives. In most cases, the bond strengths obtained with unmodified surfaces are more than adequate for product assembly. Adhesive bond strengths can be further enhanced by surface treatments that improve wetting, such as plasma treatment, corona treatment, light sanding, grit blasting, and chemical etching. Table 28.17 shows the effectiveness of plasma treating Vectra LCPs to promote adhesion.

Generally, filled or reinforced grades of Vectra LCP provide greater bond strengths than unfilled grades.

Table 28.18 shows typical lap shear strengths (ASTM D3163) obtained with a variety of adhesives tested at 22, 100, and 150°C (72, 212, and 302°F). Before specifying these or any other adhesives, the end user should make certain that all mechanical, thermal, electrical, chemical, and other properties of the adhesive are suitable for the application in question. It should be noted that these data are a general screening of classes of adhesives, not a specific recommendation.

Reference: *Vectra Liquid Crystal Polymer (LCP)*, Supplier design guide, Ticona, 2001.

Hoechst AG: Vectra A130

The adhesives used in this study were: PLUS CP792 (a cyanoacrylate by Permabond), Araldite AW106 + HV953V hardener (two-part epoxy by Ciba Speciality Chemicals) and AF163-2K (a modified epoxy film by 3M).

Trials were performed using three excimer lasers: XeCl (wavelength 308 nm), ArF (wavelength 193 nm) and KrF (wavelength 248 nm). The pulse energy of the XeCl laser was120 mJ and, for both ArF and KrF lasers, it was 100 mJ, with a pulse duration of 10–15 ns. The

Table 28.17. Adhesive Lap Shear Strengths for Plasma Treated Vectra LCPs

	Lap Shear Strength for Vectra A130 (MPa)		Lap Shear Strength for Vectra A625 (MPa)	
	Epoxy	Urethane	Epoxy	Urethane
No treatment	7.2	0.9	6.5	1.3
Oxygen plasma	11.4	9.3	11.0	6.7
Ammonia plasma	8.8	10.5	8.6	7.2

Table 28.18. Lap Shear Strengths for Adhesively Bonded Vectra LCPs

Test Temperature (°C)	Adhesive Type	Lap Shear Strength Range (N/mm^2)		Lap Shear Strength Average Value (N/mm^2)	
		As Molded	Surface Treated*	As Molded	Surface Treated*
22	2 part epoxy	3.1–6.9	5.5–14.5	4.8	9.0
	1 part epoxy	4.1–9.0	5.5–9.7	6.2	10.7
	Cyanoacrylate	2.1–4.8	3.4–6.9	3.4	5.5
	2 part acrylate	1.7–5.5	3.4–5.5	3.1	4.8
100	2 part epoxy	1.0–2.1	1.0–2.8	1.4	2.1
	1 part epoxy	1.4–4.8	1.7–5.5	3.4	4.1
	Cyanoacrylate	2.1	2.1–3.4	2.1	2.8
	2 part acrylate	0.7–1.4	1.4–2.1	1.0	1.7
150	2 part epoxy	0.7–1.4	0.7–1.4	0.7	1.0
	1 part epoxy	0.7–2.1	0.7–2.1	1.4	1.4
	Cyanoacrylate	0.2–0.3	0.3–0.7	0.2	0.7
	2 part acrylate	0.3	0.7	0.3	0.7

*Light sanding or grit blasting and solvent wash.

beams were focused through a 500 mm (19.7 inch) focal length mirror to produce a rectangular area of 6 × 3 mm (0.24 × 0.12 inches) on the adherend. For each specimen, a treated width of approximately 25 mm (1 inch) was produced.

Results of this work have shown that the ArF and KrF laser treatment resulted in improvement in adhesion; the ArF laser being more effective than the KrF laser.

Laser-treated LCP adherends provided high retention (73%) of joint strength after exposure to 70°C (158°F) and 95%RH for three weeks.

Reference: Tavakoli SM, Riches ST: Laser surface modification of polymers to enhance adhesion. Part II—PEEK, APC-2, LCP and PA. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

Hoechst AG: Vectra

Bonding with adhesives can be successful, especially if suitable pretreatment operations such as mechanical surface roughening, etching with chromosulfuric acid, or low pressure plasma treatment are carried out. Suitable adhesives for bonding Vectra are given in Table 28.19.

Selection of the correct adhesive depends on the service conditions that the bonded molding will encounter and on a variety of other factors. Preliminary trials and close contact with the adhesives industry are recommended in each case.

Reference: *Vectra Polymer Materials*, Supplier design guide (B 121 BR E 9102/014), Hoechst AG, 1991.

28.3.9 Mechanical Fastening

Ticona: Vectra

Staking: Hot staking is the preferred way to form a ‘head’ on a boss or rivet made from Vectra LCPs. Typically, a very hard surface is recommended for the heated forming tool to reduce wear when heading bosses in parts molded from the most often used Vectra LCP glass-reinforced resins. Heating rates and temperatures are similar to those used with other semicrystalline or amorphous thermoplastics like polyesters, nylons, and polycarbonates.

Table 28.19. Adhesive Systems that Can be Used to Bond Vectra LCP

Adhesive system	Basis
Two-pack adhesives	Epoxy resin Methacrylate Polyurethane
Single-pack adhesive	Cyanoacrylate Hot-melt adhesives

Cold staking is not recommended for Vectra LCPs, since the resin is too hard and brittle to form without being heated and softened or melted.

Screws: Vectra LCPs can be used for producing parts that will be joined together by screw coupling. Trials were done to create the design and evaluate the ratio of screw/hole dimensions. The screw hole diameter must be designed with very narrow tolerances. Table 28.20 gives typical dimensions for a screw.

Ultrasonic Inserts: The Ultrasert II insert from Heli-coil has stepped inclined ribs that continually present new metal surfaces to the plastic, thus forming a continuous zone of melting and solidifying during installation. This creates a homogeneous structure around the insert. The Ultrasert II has a unique knurled flange, which provides positive downward compressive force to the molten plastic that assures complete filling of the grooves for torque resistance. Table 28.21 gives the performance of these inserts in Vectra LCP.

Reference: *Vectra Liquid Crystal Polymer (LCP)*, Supplier design guide, Ticona, 2001.

Hoechst AG: Vectra

If snap-fit joints are to be used in Vectra moldings, then consideration must be given to the product's relatively low extensibility. Maximum strain during assembly should be restricted to about half the elongation at break. For this reason, barbed-leg snap-fits, for example, designed as flexible springs are an advantage because they can readily accommodate strain through variation in length and thickness. Weld lines in the strained zone are inadvisable because they can break during assembly.

Reference: *Vectra Polymer Materials*, Supplier design guide (B 121 BR E 9102/014), Hoechst AG, 1991.

Table 28.20. Typical Boss Dimensions for Vectra LCPs

Material	Screw Type (EJOT)	Hole Diameter	Boss Diameter	Screwing Depth
Vectra A130	PT	0.84 d	1.9 d	1.8 d
Vectra E130i	PT	0.86 d	1.9 d	1.8 d
Vectra B230	PT	0.90 d	2.0 d	1.9 d

d: nominal screw diameter.

Table 28.21. Performance of Dodge Ultrasert II Molded-in Inserts for Vectra LCPs

Thread Size	Part Number	Tensile Strength (N)	Rotational Torque (Nm)	Jack-out (Nm)
#2–56	6035-02BR115	420.5	0.9	0.3
	6035-02BR188	987.9	1.1	0.4
#4–40	6035-04BR135	842.4	2.8	1.0
	6035-04BR219	1764.4	2.9	1.7
#6–32	6035-06BR150	1067.1	3.2	0.8
	6035-06BR250	2182.2	3.4	1.9
#8–32	6035-2BR185	1359.5	3.8	2.0
	6035-2BR312	2247.3	5.7	2.9
#10–32	6041-3BR225	1659.0	6.3	3.7
Ultrasonic insertion conditions (Branson ultrasonic welder, model 8700)				
Thread size	**Booster**	**Weld Time (s)**	**Hold Time (s)**	**Air Pressure (MPa)**
#2	Black	0.4	0.5	0.10
#4	Black	0.5	0.5	0.10
#6	Black	0.6	0.5	0.14
#8	Black	0.6	0.5	0.14
#10	Black	0.7	1.0	0.14

28.4 Polycyclohexylenedimethylene Ethylene Terephthalate

28.4.1 Solvent Welding

Eastman: Kodar 6763 (features: transparent)

In tests conducted to evaluate the bondability/compatibility of plasticized PVC tubing to rigid, transparent thermoplastics, luers molded out of PETG were generally more difficult to assemble than those made from other materials. However, this was not a factor where at least 50% cyclohexanone was used. Each solvent except acetone resulted in exceptional bond strengths. No crazing was observed with any solvent or solvent mixture. Either a 50:50 blend of methylene chloride in cyclohexanone or a 50:50 blend of MEK in cyclohexanone is suggested for use with PETG.

Reference: Haskell A: Bondability/compatibility of plasticized PVC to rigid, transparent thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

28.5 Polyethylene Naphthalate

28.5.1 Vibration Welding

Shell Polyester: PEN

The influence of process conditions on the structure developed in the HAZ of vibration welded injection-molded amorphous polyethylene 2,6-naphthalene dicarboxylate (PEN) was studied using optical microscopy and matrixing microbeam X-ray diffraction. The structural gradients developed in the HAZ were found to be highly dependent on the process conditions; particularly, the normal force, the welding time, and weld frequency. As a result of significant shearing occurring at the interface, the naphthalene planes are oriented parallel to the weld interface. This had a detrimental effect on the mechanical performance of the parts.

Reference: Cakmak M, Robinette J: Structure development at the heat affected zones of N vibration welded poly ethylene naphthalate (PEN) parts. ANTEC 1997, Conference proceedings, Society of Plastics Engineers, Toronto, May 1997.

28.6 Polylactic Acid

28.6.1 Heat Sealing

Unitika: PLA teramac TF-25 (form: 25 μm bi-oriented film)

Effects of heat-sealing temperature and holding time on mechanical properties of heat-sealed parts of poly(lactic acid) (PLA) films were investigated. The heat sealing temperature was varied from 115 to 155°C (239–311°F). The temperature was kept at the set temperature isothermally for 0.1, 0.5, and 1.0 second, and the films were cooled down to room temperature for 5 seconds. The pressure was kept at 0.42 MPa (61 psi) throughout.

The longer holding time of 1.0 second led to higher peel strengths at heat sealing temperatures higher than 125°C (257°F). The specimens heat sealed at 115°C (239°F) showed peel strengths lower than 3 N/15 mm irrespective of holding time. The heat-sealing temperature of 125°C (257°F) led to peel strengths higher than 3 N/15 mm with smaller deviation, and peel strength was almost constant at heat-sealing temperatures above 135°C (275°F) for holding times of 0.1 and 0.5 seconds. However, further increase in peel strength could be seen in the samples heat-sealed for 1.0 second at temperatures above 135°C (275°F). It is worthy to note that the deviation of peel strength obtained at a heat-sealing temperature of 125°C (257°F) was much smaller compared to that obtained at higher heat-sealing temperatures, and the longer heat-sealing time also led to smaller deviations in peel strength.

Reference: Hashimoto Y, Hashimoto Y, Tsujii T, Kitagawa K, Kotaki M, Ishiaku US, Hamada H: Effect of heat-sealing temperature and holding time on mechanical properties at heat-sealed poly(lactic acid) films. ANTEC 2006, Conference proceedings, Society of Plastics Engineers, Charlotte, May 2006.

Unitika: PLA teramac TF-25 (form: 25 μm bi-oriented film)

In this study, the effect of heat-sealing temperature on the fracture behavior of heat-sealed PLA films was investigated. The heat sealing was carried out at sealing temperatures of 110–150°C (230–302°F) and a holding time of 0.1 seconds after reaching the maximum temperature. The temperature was kept at the set temperature for 0.1 seconds after reaching the maximum temperature, and the films were cooled for 5 seconds.

The pressure was kept at 0.3 MPa (43 psi) throughout the heat-sealing process. The peel tests were carried out by peeling open 180° from the heat-sealed part under a crosshead speed of 300 mm/minute with a 50 mm (1.97 inch) gauge length.

Effective heat sealing was not achieved at 120°C (248°F). At temperatures above 125°C (257°F), peel strengths higher than 3 N/15 mm were obtained. The peel strength became constant in the temperature range of 127.5–130°C (261.5–266°F) and then decreased above 135°C (275°F).

Reference: Konishi R, Hashimoto Y, Hashimoto Y, Anan M, Tsujii T, Morimoto M, Kitagawa K, Ishiaku US, Kotaki M, Hamada H: Fracture behavior of heat-sealed poly(lactic acid) films. ANTEC 2006, Conference proceedings, Society of Plastics Engineers, Charlotte, May 2006.

Unitika: PLA teramac TF-25 (form: 25 μm film)

The heat-sealing temperature was varied between 120 and 180°C (248 and 356°F), as selected on the dial gauge. The temperature was kept at the set temperature isothermally for 0.1 seconds and films were cooled down to room temperature for 5 seconds. The pressure was kept at 0.42 MPa (61 psi) throughout the heat-sealing procedure.

Based on the results from peeling tests, tensile tests with a circle notch, and DSC measurements, the optimum heat seal temperature was ascertained to be between 130 and 135°C (266 and 275°F). This range is narrower than most common films. It follows that the heat-sealing temperature should be carefully selected, but exact temperature management is generally difficult for the current generation of auto sealers.

Reference: Hashimoto Y, Tetsuya T, Kazuo K, Mizoguchi M, Fujita Y, Hamada H, Ishiaku US: Effect of heat-sealing temperature on mechanical properties at heat-sealed parts in biodegradable plastic film. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

29 Polyetherimide

29.1 General

GE Plastics: Ultem

Parts molded of Ultem resin can be assembled with all common thermoplastic assembly methods.

Reference: *Ultem Design Guide,* Supplier design guide (ULT-201G (6/90) RTB), General Electric Company, 1990.

29.2 Heated Tool Welding

GE Plastics: Ultem 1000 (form: injection-molded plaque)

In these experiments, the outflow in the melting phase was controlled by means of stops, the thickness of the molten film was controlled by the heating time, and the outflow during the final joining phase was also controlled by displacement stops.

Within the range of weld process parameters investigated, the highest weld strength achieved in the 3.2 mm (0.126 inch) thick material, obtained at a weld penetration of 0.66 mm (0.026 inches) and a melt penetration of 0 mm, was 84% of the base material strength.

For the 6.2 mm (0.244 inch) thick material, the highest weld strength was 85% of parent, and was obtained at a weld penetration of 0.91 mm (0.036 inches). For this value of weld penetration, relative weld strengths in the range 80–85% could be obtained over a wide heated tool temperature window of 395–440°C (743–824°F) for melt and seal times of 20 seconds and 10 seconds, respectively, and a melt penetration of 0.13 mm (0.005 inches).

While heated tool welding can produce strong welds, it requires careful dimensional and heated tool temperature control, and a continuous cleaning of the heated tool surface.

Reference: Stokes VK: A phenomenological study of the hot-tool welding of thermoplastics. Part 3: polyetherimide. *Polymer,* 42(2), p. 775, 2001.

GE Plastics: Ultem 1000 (form: injection-molded plaque)

High strengths can be attained in heated tool welds between very dissimilar materials. In heated tool welds of polyetherimide to the semicrystalline polyester PBT, weld strengths equal to 90% of the strength of PBT are obtainable. The use of different heated tool temperatures is important for obtaining high strengths in welds between dissimilar materials. The heated tool temperatures varied from 371 to 427°C (700–800°F) for polyetherimide and from 260 to 302°C (500–575°F) for PBT. In addition to the heated tool temperatures, the weld strength also depends on the melt time.

Although the two immiscible, amorphous polymers polycarbonate and polyetherimide have glass transition temperatures of 150°C (302°F) and 215°C (419°F), respectively, weld strengths comparable to the strength of polycarbonate can be attained.

High relative strengths are obtained for heated tool temperatures in the range of 371–399°C (700–750°F) for polyetherimide. Relative strengths at a polyetherimide heated tool temperature of 427°C (800°F) appear to vary erratically. This could be due to degradation of polyetherimide at this high temperature and deposits on the heated tool surfaces, affecting the cleanliness of the molten plastic layers.

Reference: Stokes VK: Experiments on the hot tool welding of dissimilar thermoplastics. ANTEC 1993, Conference proceedings, Society of Plastics Engineers, New Orleans, May 1993.

29.3 Ultrasonic Welding

GE Plastics: Ultem

The most important element in designing Ultem resin parts for ultrasonic welding is the joint design. There are three major requirements for the joint area:

- A small initial contact area (a point or a line)—energy director
- Uniform contact
- A means of alignment

The following recommendations should also be observed to achieve the best results:

- Allow for the flow of molten material.
- Locate the joint as close as possible to the point where the ultrasonic horn can be applied.
- Provide a suitable horn contact area.

- Provide proper proportioning of joint elements—avoid tight joints and large mating surfaces.
- Allow for a slight dimensional change around the perimeter of the joint.
- Use rigid fixturing or nesting of the bottom part to insure a strong weld.

Weldability is dependent upon the concentration of the vibratory energy per unit area. Since Ultem resin has a higher melting point than most other thermoplastics, more energy is required to cause the material at the joint to flow. Therefore, the energy director for welding Ultem resin parts should be fairly tall with a minimum height of 0.020 inches (0.50 mm) and a width of 0.025 inches (0.65 mm). Typical ultrasonic welding parameters for Ultem polyetherimide are given in Table 29.1.

Reference: *Ultem Design Guide*, Supplier design guide (ULT-201G (6/90) RTB), General Electric Company, 1990.

Table 29.1. Typical Ultrasonic Welding Machine Settings Used for Ultem Polyetherimide Resin

Control	Setting
Sonic time (s)	0.5–1.5
Delay time (s)	0.2–0.6
Amplitude (dial)	6–7
Dwell time (s)	0.5–2.0
Line pressure (psi)	30–60
Line pressure (MPa)	0.2–0.4

29.4 Vibration Welding

GE Plastics: Ultem 1000 (form: 6.1 mm (0.24 inch) thick injection-molded plaque)

PEI welds extremely well to PBT; welds with strengths of 95% of the strength of PBT have been demonstrated for the following welding conditions: frequency of 120 Hz, amplitude of 3.175 mm (0.125 inches), pressure of 0.90 MPa (130 psi), weld penetration of 0.57–1.35 mm (0.022–0.053 inches) and a weld time of 2.7–4.4 seconds; or frequency of 400 Hz, amplitude of 0.635 mm (0.025 inches), pressure of 3.45 MPa (500 psi), weld penetration of 1.33 mm (0.052 inches) and a weld time of 4.1 seconds.

PEI also welds well with Valox HV7065, a polyester blend containing about 65 wt.% mineral filler; welds with strengths of about 92% of the tensile strength of Valox HV7065 have been demonstrated using the following welding conditions: weld frequency of 120 Hz, weld amplitude of 3.175 mm (0.125 inches), weld pressure of 3.45 MPa (500 psi), weld penetration of 0.54–1.30 mm (0.021–0.051 inches) and a weld time of 1.0–2.1 seconds.

Reference: Stokes VK: The vibration welding of poly-(butylene terephthalate) and a polycarbonate/poly(butylene terephthalate) blend to each other and to other resins and blends. *Journal of Adhesion Science and Technology*, 15(4), p. 499, 2001.

GE Plastics: Ultem 2300 (features: 6.35 mm (0.25 inches) thick; form: injection-molded plaque; reinforcement: 30% glass fiber)

The highest weld strengths obtained at weld frequencies of 120, 250, and 400 Hz were 72.3, 78.8, and 74.2 MPa (10,500, 11,400, and 10,800 psi), respectively. With a mean tensile strength of 124.35 MPa (18,035 psi) for the glass-filled resin, these three weld strengths correspond, respectively, to relative weld strengths of 58, 63, and 60%. The best weld strengths were obtained at high frequencies and high weld pressures. For the range of weld process conditions studied here, the optimum conditions appear to be a weld frequency of 250 Hz, a weld amplitude of 0.889 mm (0.035 inches), and a weld pressure of 3.45 MPa (500 psi). At these conditions, a weld strength of about 79 MPa (11,500 psi), with a failure strain of about 1.3%, can be attained.

Reference: Stokes VK: Vibration weld strength data for glass-filled polyetherimide. *Journal of Adhesion Science and Technology*, 15(4), p. 1763, 2001.

GE Plastics: Ultem 1000 (features: 6.35 mm (0.25 inches) thick; manufacturing method: injection molding; form: injection-molded plaque)

At a welding frequency of 120 Hz, the cross-thickness weld strength increases with the weld amplitude and the weld pressure, and the threshold penetration is larger than for the normal-mode welding of this material. Weld strengths at penetrations of about 0.5 mm (0.02 inches) are significantly higher than for penetrations of the order of 0.3 mm (0.012 inches). The critical penetration threshold therefore lies in the range of 0.3–0.5 mm (0.012–0.02 inches). Although both the strength and the strain-to-failure increase with the weld pressure, the highest strengths attained for 120 Hz welds are significantly lower than the strength of PEI, just as in normal-mode welding.

At the higher frequency of 250 Hz, excellent cross-thickness weld strength can be achieved in PEI, and the optimum conditions are the same as for normal-mode welds.

Reference: Stokes VK: Cross-thickness vibration welding of polycarbonate, polyetherimide, poly (butylene terephthalate) and modified polyphenylene oxide. *Polymer Engineering and Science,* 37(4), p. 715, April 1997.

GE Plastics: Ultem 1000 (features: 6.4 mm (0.252 inches) thick; manufacturing method: injection molding; form: injection-molded plaque)

This study showed that, under the right conditions, very high strengths and ductilities can be achieved in polycarbonate to polyetherimide vibration-welded joints. These joints can attain the strength of PC, the weaker of the two materials.

However, the conditions for achieving high strengths are different from those for neat resins, and cannot be determined from penetration-time curves alone. In neat resins, high strengths are achieved once the penetration rate reaches a steady state, so that penetration-time curves can be used for determining optimum welding conditions. On the other hand, because of differences in “melt” temperatures and viscosities, the apparent steady-state conditions indicated by penetration-time curves for PC to PEI welds are deceptive. The process is dominated by the high melting and flow rates of PC, which masks the still-developing melt and flow conditions in PEI when an apparent steady state has been attained. As a result, weld strength continues to increase with penetration, even when this penetration falls in the steady-state regime. Because of this, additional information is required for optimizing PC to PEI welds.

Scanning electron microscopy studies have demonstrated that the dominant mechanism for bond strength during the early stages of welding is the mechanical interlocking at the weld interface produced by shear mixing of the two molten polymers. Process conditions affect the thickness and structure of the zone over which this mixing and interlocking occurs.

The fracture surfaces of PC to PEI welds are interesting. The high-strength welds have deep ridges on both halves of the fracture interface. The depth of the ridges and the strength appear to increase with the weld pressure. There is a major difference between low-frequency and high-frequency welds. AT 120 Hz, the ridges are perpendicular to the direction of the vibratory motion. Although nominally parallel, these ridges exhibit a “wavy” structure. On the other hand, at frequencies equal to 250 Hz and 400 Hz, the ridges are parallel to the direction of motion. The ridge structure is also more parallel and better defined. These well-defined ridges, which appear in the high-frequency (low-amplitude) welds, are probably caused by flow instabilities.

Reference: Stokes VK, Hobbs SY: Strength and bonding mechanisms in vibration-welded polycarbonate to polyetherimide joints. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

GE Plastics: PEI

The achievable strengths of vibration welds of PEI to itself and to other thermoplastics are given in Table 29.2.

Reference: Stokes VK: Toward a weld-strength data base for vibration welding of thermoplastics. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

29.5 Resistive Implant Welding

GE Plastics: Ultem 1000 (form: laminate; reinforcement: glass fiber, carbon fiber)

Sufficient electrical insulation between the heating element and carbon-fiber-reinforced PEI (CF-PEI) laminates, using a glass-fiber-reinforced PEI (GF-PEI) interlayer, eliminated current leakage to the laminate. The nonuniformity of heat transfer introduced a high temperature gradient in the vicinity of the penetration area of about 25% of the weld length. Using a simple criterion, based on the temperature amplitude between the degradation temperature and the glass-transition temperature, maximum weld lengths of 370 mm (14.6 inches) were extrapolated. Large width lap shear specimens made from GF-PEI laminates or GF/CF-PEI laminates were successfully welded using unidirectional heating elements. Lap shear strength values obtained exceeded the compression-molded benchmarks of the CF-PEI laminates. Meanwhile, the interlaminar fracture toughness of resistance welded double cantilever beam (DCB) specimens amounted to 85% and 90% of the compression-molded baselines of the CF-PEI DCB laminates with unidirectional and fabric interlayers, respectively.

Table 29.2. Achievable Strengths of Vibration Welds of Polyetherimide to Itself and to Other Thermoplastics

Material Family	**PEI**				
Tensile strength[b], MPa (ksi)	119 (17.3)				
Elongation @ break[b], %	6				
Specimen thickness, mm (in.)	6.3 (0.25)				
Mating material					
Material family[a]	ABS	M-PPO	PC	PBT	PEI
Tensile strength[b], MPa (ksi)	44 (6.4)	45.5 (6.6)	68 (9.9)	65 (9.5)	119 (17.3)
Elongation @ break[b], %	2.2	2.5	6	3.5	6
Specimen thickness, mm (in.)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)
Process parameters					
Process type	Vibration welding				
Weld frequency	120 Hz	120 Hz	120 Hz	120 Hz	250–400 Hz
Welded joint properties					
Weld factor (weld strength/weaker virgin material strength)	0.65	0	0.95	0.95	1.0[c]
Elongation @ break[b], % (nominal)	1.14		2.75	4.1	6

[a] ABS: acrylonitrile-butadiene-stryrene copolymer; M-PPO: modified polyphenylene oxide; PC: polycarbonate; PBT: polybutylene terephthalate; PEI: polyetherimide.

[b] Strain rate of $10^{-2}s^{-1}$.

[c] High strength can only be achieved through high frequency welds.

Reference: Ye L, Ageorges C: Large scale resistance welding of thermoplastic composites: feasibility and limitations. Composites from fundamentals to exploitation. 9th European Conference (ECCM), Brighton, UK, June 2000.

29.6 Solvent Welding

GE Plastics: Ultem

Solvent welding is one of several alternatives for joining Ultem resin parts. The end result of the process after the solvent has evaporated is a true resin-to-resin weld with no intermediate material. Methylene chloride, or a 1–5% solution of Ultem resin in this solvent, is recommended for bonding parts molded of Ultem resin.

Reference: *Ultem Design Guide*, Supplier design guide (ULT-201G (6/90) RTB), General Electric Company, 1990.

GE Plastics: Ultem 1000 (features: general purpose grade)

Figure 29.1 provides a representative sample of the bond strength that can be achieved with Ultem 1000 polyetherimide resin adhered to flexible polyvinyl chloride (PVC). Of the solvents, the cyclohexanone appeared to withstand the greatest load before joint failure.

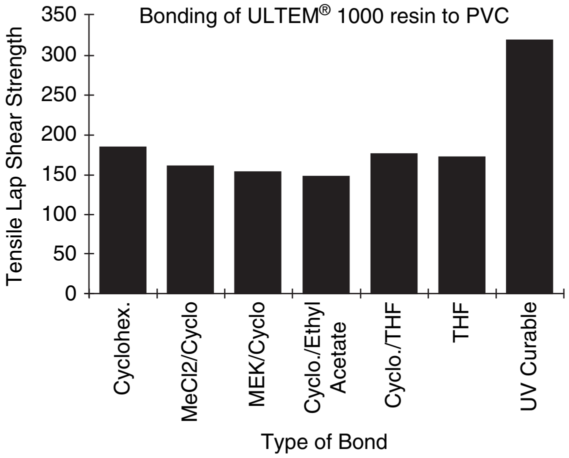


Figure 29.1. Adhesive and solvent bond strengths of Ultem 1000 polyetherimide resin adhered to Alpha Chemical PVC 2235L85 flexible polyvinyl chloride (PVC). (Solvents: $MeCl_2$: methylene chloride; MEK: methyl ethyl ketone; cyclo: cyclohexanone; THF: tetrahydrofuran. Note: solvent combinations are 50:50 solutions).

Reference: *Guide to Engineering Thermoplastics for the Medical Industry*, Supplier design guide (MED-114), General Electric Company.

29.7 Adhesive Bonding

GE Plastics: Ultem

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 29.3 give a good indication of the typical bond strengths that can be achieved as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the

Table 29.3. Shear Strengths of Ultem PEI to PEI Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[b]

Material Composition		**Loctite Adhesive**					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin Grade 1010	3 rms	150 (1.0)	1350 (9.3)	300 (2.1)	1100 (7.6)	500 (3.5)	2250 (15.5)
Grade 1010 roughened	47 rms	1050 (7.2)	2450 (16.9)	2000 (13.8)	2000 (13.8)	800 (5.5)	2250 (15.5)
Grade 2100	10% glass reinforced	350 (2.4)	1050 (7.2)	500 (3.5)	900 (6.2)	700 (4.8)	1750 (12.1)
Grade 2400	40% glass reinforced	1150 (7.9)	1000 (6.9)	850 (5.9)	2150 (14.8)	1700 (11.7)	1300 (9.0)
Grade 3453	45% glass/silica reinforced	1300 (9.0)	1650 (11.4)	1350 (9.3)	2000 (13.8)	1500 (10.3)	1500 (10.3)
Grade 4001	Unreinforced, with lubricant	150 (1.0)	650 (4.5)	300 (2.1)	700 (4.8)	550 (3.8)	>1800[a] (>12.4)[a]
Grade CRS500l	Unreinforced, chemically-resistant grade	450 (3.1)	1400 (9.7)	200 (1.4)	1050 (7.2)	700 (4.8)	1550 (10.7)
Grade 7801	25% carbon reinforced	950 (6.6)	1250 (8.6)	1350 (9.3)	1850 (12.8)	750 (5.2)	1400 (9.7)
Grade LTX100A	PEI/PC blend injection molding grade	750 (5.2)	1400 (9.7)	650 (4.5)	1100 (7.6)	800 (5.5)	3550 (24.5)

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

bondability of a material. In addition, the additives and fillers were tested individually in Table 29.3, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Flashcure 4305 light cure adhesive achieved the highest bond strengths on the PEI, typically achieving substrate failure. Prism 401, Prism 4011 medical device and Super Bonder 414 instant adhesives, Loctite 3105, a light curing acrylic adhesive, Hysol E-90FL and E-30CL epoxy adhesives, Hysol 3631 hot melt adhesive and Fixmaster high performance epoxy normally achieved the highest bond strengths on the various grades of Ultem that were evaluated. However, the performance of each adhesive varied from grade to grade. Loctite 3340 light cure adhesive typically achieved the lowest bond strengths on PEI.

Surface Treatments: Surface roughening caused large, statistically significant increases in the bond strengths achieved on PEI. The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused a significant decrease in the bond strengths achieved on most of the grades of Ultem that were evaluated.

Other Information: Good solvents for use with PEI are methylene chloride and n-methylpyrrolidone. An accelerator may be necessary to speed the cure of cyanoacrylates on unfilled grades of PEI. Some grades of PEI have been found to be incompatible with cyanoacrylate adhesives. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

GE Plastics: Ultem

Ultem resin parts can be bonded either together or to dissimilar materials by a wide variety of commercially available adhesives. Because adhesive bonding involves the application of a chemically different substance between two parts, the end-use environment of the assembled unit is important in selecting an adhesive. Service temperatures, environments and desired performance must all be taken into consideration. Good adhesion can be effected by simple solvent wipe, but surface activation by corona discharge, flame treatment, or chromic acid etch is sometimes desirable.

Reference: *Ultem Design Guide*, Supplier design guide (ULT-201G (6/90) RTB), General Electric Company, 1990.

GE Plastics: Ultem 1000 (features: general purpose grade)

Figure 29.1 provides a representative sample of the bond strength that can be achieved with Ultem 1000 polyetherimide resin adhered to flexible polyvinyl chloride (PVC). The UV-curable adhesive yielded the highest bond strength with the Ultem resin and PVC combination. However, if the UV-curable adhesives are used with Ultem resins, the UV light must be transmitted through the material it is bonded to, and not through the Ultem resin.

Reference: *Guide to Engineering Thermoplastics for the Medical Industry*, Supplier design guide (MED-114), General Electric Company.

29.8 Mechanical Fastening

GE Plastics: Ultem 1000 (features: natural resin, transparent, amber tint); **Ultem 2100** (features: flame retardant; material composition: 10% glass-fiber reinforcement; process type: injection molding); **Ultem 2200** (features: flame retardant; material composition: 20% glass-fiber reinforcement; process type: injection molding); **Ultem 2300** (features: flame retardant; material composition: 30% glass-fiber reinforcement; process type: injection molding)

Snap-fit Assemblies: The ductility and strength of Ultem resin make it ideally suited to snap-fit assembly.

When designing flexing fingers, do not exceed the recommended strains shown in Table 29.4. The secant modulus at the operating strain should be used to calculate cantilever force or stress.

Staking: Ultrasonic staking is the process of melting and reforming a ridge of Ultem resin to mechanically fasten another component of an assembly. A hole in that component receives an Ultem resin stud molded into the plastic part. The surface of the stud is vibrated out-of-phase with a horn using high amplitude and a relatively small contact area. The vibrations cause the progressive melting of the plastic under continuous light pressure, reforming the stud in the configuration of the horn tip. Tip configuration of the horn will depend upon the application, the grade of resin and the stud design. Either standard or low profile staked head-forms are satisfactory for most applications. While the low profile head-form offers an appearance advantage over the standard head-form, the latter provides approximately three times the strength of the low profile head-form. Rigid support of the Ultem resin part is required during the staking operation.

Tapping and Self-tapping Screws: Self-tapping screws are suitable with Ultem resin components. Self-tapping screws form or cut as they are driven into the molded part, thus eliminating the need for a molded-in thread or a secondary tapping operation. There are two general classes of self-tapping screws: thread-cutting and thread-forming. Both classes have advantages and disadvantages depending on the particular application. Thread-cutting screws provide lower boss stresses since the material is not excessively displaced; however cutting the plastic results in lower driving torque, stripping torque and pull-out strength. Thread-forming screws produce higher boss stresses, yet higher driving torque, stripping torque and pull-out strength can generally result. The recommended screw type is best determined by prototype testing.

Table 29.4. Recommended Permissible Strains for Use in Designing Snap-fits with Different Grades of GE Plastics Ultem Polyetherimide

Ultem Resin Grade	Permissible Strain %	Secant Modulus at Permissible Strain
1000	5.25	1860 MPa
2100	2.5	3789 MPa
2200	1.5	Tensile modulus
2300	1.5	Tensile modulus

Molded-in Inserts: Molded-in threaded inserts may be used with all grades of Ultem resin. Recommendations for achieving maximum strength are:

- Smooth inserts should be used where design allows.
- Use simple pull-out and torque retention grooves when high torque and pull-out retention are required.
- If a knurled insert is used, keep the size of knurls to a minimum.
- High mold temperatures should be used to reduce thermal stresses around the insert.
- Sufficient material should be provided around the insert to maintain high strength (Table 29.5).

Pretesting of assemblies is recommended to determine their suitability in actual end-use environments.

Molded-in Threads: Ultem resin is increasingly being specified for external and internal molded threads. The unique combination of high modulus, strength, coefficient of friction and low stress relaxation yields higher torque values per turn, higher fracture torques and lower torque relaxation. Thread forms commonly used with Ultem resin parts include all the straight thread standards (e.g., UNC and UNF) plus the tapered thread standards (e.g., NPT and NPTF). Threads produced with solid unscrewing cores may offer greater accuracy. Any sealing compound that is used must be tested for compatibility with the Ultem resin grade to determine if the combination of stress and sealant causes failure below expected strengths.

Ultrasonic Inserts: Ultrasonic insertion is recommended for fast and economical anchoring of metal inserts. This technique provides a high degree of mechanical reliability with excellent pull-out and torque retention. Furthermore, under proper design, ultrasonic insertion results in lower residual stresses compared to other methods of insertion, since it insures a uniform melt and minimal thermal shrinkage.

Reference: *Ultem Design Guide*, Supplier design guide (ULT-201G (6/90) RTB), General Electric Company, 1990.

Table 29.5. Ratio of Wall Thickness to Outside Diameter (OD) of Molded-in Inserts in Ultem Polyetherimide

Insert Material	Ratio of Wall Thickness to OD
Steel	1.0
Brass	0.9
Aluminum	0.8

30 Polyethylenes

30.1 Polyethylene General

30.1.1 General

BASF AG: Lupolen

Lupolen PE-HD and PE-MD blow moldings can be bonded together by the application of heat and pressure. They can also be bonded by this means to injection moldings and extruded or thermoformed articles. The materials from which the various parts have been produced should have roughly the same melt viscosity, an idea of which can be obtained from the melt index.

Reference: *Lupolen Polyethylene and Novolen Polypropylene Product Line, Properties, Processing*, Supplier design guide (B 579 e / 4.92), BASF Aktiengesellschaft, 1992.

BASF AG: Lupolen

Lupolen and Lucalen moldings and film can be welded together by the application of heat and pressure. Examples of the techniques that can be adopted are vibration, ultrasonic, friction, hot gas, and hot plate welding.

Film can be heat sealed by slit-seal, thermal contact and thermal impulse techniques. The main factors that govern the quality of the seam are temperature, pressure, and time.

Reference: *Lupolen, Lucalen Product Line, Properties, Processing*, Supplier design guide (B 581 e/(8127) 10.91), BASF Aktiengesellschaft, 1991.

PE

It was shown that ultrasonic, induction and infrared heating are some of the best choices for the sealing of aseptic food packages. CO_2 and YAG lasers provide for fast melting of the polyethylene film, but do not shorten the cycle time sufficiently to justify their high price. Ultrasonic sealing provides a short cycle time of less than 0.5 seconds and very consistent seal quality with peel strengths being limited by failure in the cardboard. Discontinuities in the aluminum foil always occur during ultrasonic sealing of the package material. Additional work is needed to determine the effects of the discontinuities in the aluminum foil on the integrity of the food. Induction sealing also provides a short cycle time of less than 0.5 seconds with consistent failure in the cardboard. Because of the low holding pressure, the aluminum foil remains intact. The cycle time for infrared sealing is longer because it is a two-step process. Under the optimal sealing conditions, the aluminum foil remains intact. Infrared is more suitable for continuous sealing.

Reference: Yeh HJ, Benatar A: Methods for sealing of aseptic food packages. ANTEC 1991, Conference proceedings, Society of Plastics Engineers, Montreal, May 1991.

30.1.2 Heated Tool Welding

PE (form: pipe)

Polyethylene is permeable to methane and other hydrocarbons. However, the rate of diffusion through the pipe walls is small enough that no significant amount of gas is lost, and there are no public or operational safety issues.

Field crews employed by Northern States Power, a company that supplies gas and electricity to central Minnesota, have occasionally noticed an anomaly during heat fusion joining where, at the end of the heating phase, just prior to fusion, the heated surfaces appeared to be uneven because of bubbles in the melted surface. After the joining was complete, the bubbles were visible in the bead.

The Gas Research Institute initiated an investigation and it was shown that PE gas distribution piping could absorb higher hydrocarbons like propane, and release them in the heating phase of fusion joining. It was also shown that the strength of these “bubbly” joints could be significantly less than that of normal joints, depending on the amount of absorbed material present.

It is recommended that, to avoid degradation of fusion quality, the concentration of propane in PE should not exceed 0.2%.

Reference: Pimputkar SM, Belew B, Mamoun MM, Stets JA: Strength of fusion joints made from polyethylene pipe exposed to heavy hydrocarbons. Plastics Piping Systems for Gas Distribution, Conference proceedings, October 1997.

30.1.3 Ultrasonic Welding

BASF AG: Lupolen

Ultrasonic welding of polyethylene is restricted to the near field.

Reference: *Lupolen Polyethylene and Novolen Polypropylene Product Line, Properties, Processing*, Supplier design guide (B 579 e / 4.92), BASF Aktiengesellschaft, 1992.

DuPont Canada: Zemid (applications: cold weather; features: homogeneous; filler: mineral)

Parts made of Zemid resins can be sonically welded, resulting in good bond strength. Lab tests have demonstrated that the bond strength has exceeded the shear strength, under the following conditions:

Amplitude	0.08 mm (0.003 inches) @ 20 kHz
Time	0.4 s
Energy	300 J (220 ft lbf)
Pressure	0.14 MPa (20 psi)

Reference: *Zemid Product Information Guide*, Supplier marketing literature (H-07490), DuPont Canada, 1990.

PE (features: 5.8 mm (0.23 inches) thick)

Most olefin fibers, woven and non-woven have good ultrasonic welding characteristics.

Reference: *Ultrasonic Sealing and Slitting of Synthetic Fabrics*, Supplier technical report, Sonic & Materials, Inc.

30.1.4 Spin Welding

PE (form: pipe)

This study describes a newly developed spin welding method for laying piping, where a short pipe is inserted between two long pipes to be laid and the short section is then rotated.

Welding tests were carried out on materials manufactured by three typical polyethylene pipe manufacturers at temperatures of –5, 23, and 40°C (–23, 73, and 104°F). Typical mechanical tests were carried out for the categories stipulated by the Japan Gas Association in conformity to the JIS standards.

The results indicated that welding was feasible under identical conditions even with discrepancies in the joining environment temperatures and the piping provided by the material manufacturers. In addition, the weld zone performance was seen to achieve the standard with adequate margin. The long-term stability of welds made by spin welding showed results similar to, or better than, the joint performance achieved by conventional heat fusion welding.

Reference: Takasu N: Friction welding of plastics. *Welding International*, 17(11), p.856, 2003.

PE (form: pipe)

This study details an investigation into the effect of friction welding parameters on polyethylene pipe joints. Results showed that the initial torque, steady torque, and total loss increased with an increasing friction pressure. The upset length proportions on the rotation and fixed sides differed depending on the friction welding conditions. The conditions that produced favorable weld appearance had a much narrower range than for carbon steel. Also, during friction welding of polyethylene, the working environment is substantially impaired by scattering of flocculent and liquefied polyethylene and by smoke and bad odor generation.

Reference: Hasegawa M, Asada T, Ozawa Y: Study of friction welding of polyethylene. *Welding International*, 16(7), p. 537, 2002.

PE (form: pipe, 60 mm (2.36 inches) outside diameter)

An investigation of the effects of the friction welding conditions on the joining phenomena and tensile strength of welded joints produced from polyethylene gas supply pipes was carried out. The spin welding parameters studied were:

- Friction pressure: 0.4 MPa (58 psi).
- Friction time: 10 seconds.
- Upset pressure: 0.4 MPa (58 psi).
- Upset time: 60 seconds.
- Rotational speed: 20–50 seconds^{-1}.

The results showed that the friction pressure strongly affected the initial torque and total loss in such a way that the initial torque and total loss increased sharply with increasing friction pressure. The initial torque and upset pressure found during friction welding of polyethylene pipes were much lower than those found during friction welding of metals. The friction pressure strongly affected the flash size on the outside and inside of the pipes in such a way that the flash size (height and width of flash) increased sharply with increasing friction pressure. The friction pressure and rotational speed strongly affected the appearance of the friction-welded joints. The tensile strength of sound friction-welded joints was equivalent to that of base polyethylene pipes. The elongation at tensile fracture, however, was slightly lower than that of the base polyethylene.

Reference: Hasegawa M, Asada T, Ozawa Y, Taki N: Study of friction welding of polyethylene pipes. *Welding International*, 12(9), p. 682, 1998.

30.1.5 Radio Frequency Welding

BASF AG: Lupolen

High frequency techniques are inapplicable, since they do not allow polyethylene to be heated to the requisite temperature. This is because the energy requirements in the high frequency field are given by the product of the dielectric constant and the dissipation factor, tan delta, and this product is very low for polyethylene.

Reference: *Lupolen Polyethylene and Novolen Polypropylene Product Line, Properties, Processing*, Supplier design guide (B 579 e / 4.92), BASF Aktiengesellschaft, 1992.

30.1.6 Laser Welding

PE

A summary of the laser welding trials carried out on polyethylene sheet is given in Table 30.1. Low power CO_2 lasers have the capability of joining thin (< 0.2 mm; 0.008 inch) plastic sheets in lap and cut/seal configurations at high speeds (50 m/min; 2.7 ft/s). Applications could include high speed packaging where a non-contact, flexible, computer controlled system would have advantages over ultrasonic, dielectric and heat sealing techniques. The Nd:YAG lasers, with lower absorption capabilities of the shorter wavelength, have potential to be applied to joining plastics in the thickness range of 0.2–2.0 mm (0.008–0.08 inches) in lap and butt joint configurations. Benefits include low distortion and low general heat input. Differences in the melting of the plastic materials and the effect of pigmentation with Nd:YAG lasers have been noted and must be examined further.

Reference: Jones IA, Taylor NS: High speed welding of plastics using lasers. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

30.1.7 Infrared Welding

PE

This study evaluated the heating characteristics of infrared energy from a quartz-halogen lamp (maximum output at 0.89 μm) on PE containing different levels of carbon black.

This work showed that absorption is very sensitive to the level of carbon black in the polymer formulation. This sensitivity occurs at very low levels of carbon black. Thus, when a polymer is selected for infrared welding, it will be important to know the concentration of carbon black in the formulation. If it falls below 0.07%, there will be an increasing depth of heating and less surface heating.

Levels in excess of 0.03% carbon will heat primarily by surface absorption of the infrared radiation. In this case, the creation of a significant depth of melting will depend on the relatively slow process of conduction. However, if changeover times are short, this latter method will approach high temperature hot plate welding where surface decomposition is tolerated so long as the decomposed material is squeezed out as flash.

Reference: Grimm RA, Yeh H: Infrared welding of thermoplastics. Colored pigments and carbon black levels on transmission of infrared radiation. ANTEC 1998, Conference proceedings, Society of Plastics Engineers, Atlanta, May 1998.

PE

Infrared welding of polyethylene pipes with a tubular radiant heater was successfully conducted. With only nine seconds of heating time, a weld strength and elongation close to the parent material was achieved. Although the weld strengths were close to the parent material over the wide range of parameters used, there were some brittle failures at very low and high heating levels due to underheating and overheating of the

Table 30.1. Summary of Laser Welding Conditions and Tensile Properties for Polyethylene Joints

Material			Laser Conditions			Tensile Properties	
Type	Thickness (mm)	Joint type	Type	Power (W)	Speed (m/min)	% of parent	Failure mode
PE	0.1	Lap	CO_2	100	16.5	>100	Parent
PE	0.1	Lap	CO_2	200	36		
PE	0.1	Lap	CO_2	300	50		
PE	0.1	Cut/seal	CO_2	100	5.7	94	Weld
PE	0.5	Lap	Nd:YAG	80	0.1	68	Weld

part surface. Weld strength should be evaluated with elongation; weld strength alone did not indicate the quality of the weld. Elongation varied with different welding parameters. It reached its peak at 9 seconds heating time, 7 mm (0.28 mm) heating distance and 334 N (75 lbf) forging force (2.7 mm (0.11 inch) bead size). Any longer heating time, shorter heating distance, and higher force (larger than 2.7 mm (0.11 inch) bead size) beyond this condition did not improve the elongation. Weld bead size can be a good indicator for heating level because it is very dependent on heating time and heating distance.

Reference: Yeh HJ: Infrared welding of polyethylene pipes using radiant heater. ANTEC 1996, Conference proceedings, Society of Plastics Engineers, Indianapolis, May 1996.

30.1.8 Adhesive Bonding

PE

A study was performed on the effect of vacuum plasma pre-treatment with respect to adhesive bond strength on PE. Two types of high strength epoxy adhesives were use: Eccobond® 2332 (a single component adhesive) and Eccobond® 45W1 (a two-component adhesive). Eccobond® 2332 was cured for 1 hour at 120°C (248°F), Eccobond® 45W1 was used in a 1:1 ratio with Catalyst 15 and was cured for 24 hours at room temperature. The plasma treated samples were glued together within one day of the plasma treatment.

Results showed that the bond strength of vacuum plasma pre-treated samples was higher than the strength of the plastic itself.

Reference: Lippens P: Vacuum plasma pre-treatment enhances adhesive bonding of plastics in an environmentally friendly and cost effective way. *Joining Plastics 2006*, Conference proceedings, London, UK, April 2006.

McMaster Carr: PE (form: sheet)

Sheet samples were cleaned using alcohol, air-dried and then roughened with 25-micron aluminum oxide powder at 276 kPa (40 psi) using a small sandblaster. After roughening, the samples were again cleaned with alcohol and bagged. Samples were plasma treated using a process time of 10 minutes in a 100% oxygen environment. The adhesive used was FDA-2 epoxy (TRA-CON, Inc., Bedford, MA).

Results showed that plasma treatment has a great impact on bond strength of epoxy to polyethylene surfaces. This positive effect of plasma treatment was seen on aged and non-aged samples. The effect of aging samples highlighted that, without plasma treatment, the accelerated aging process completely degraded the bond.

Surface roughening had a positive effect on bond strength on samples that were not exposed to plasma treatment.

Reference: Petrie SP, Bardsley EF: Epoxy adhesives: effect of plasma treatment and surface roughness on epoxy to polyethylene bond strength. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

PE

Polyethylenes can be bonded using anaerobic, cyanoacrylate, UV, epoxy and structural acrylic adhesives. For cyanoacrylate adhesive, use Permabond POP primer. For other adhesives, surface treat via flame, corona or plasma treatment equipment.

Reference: *The Engineers Guide to Adhesives*, Supplier design guide, Permabond Engineering Adhesives.

BASF AG: Lupolen

Lupolen's high resistance to solvents prevents any adhesive from solubilizing the surface of a blow molding. Consequently, only pressure-sensitive bonds can be formed. The adhesion can be improved by prior treatment of the surfaces to be bonded together, e.g., by exposure to a flame or corona discharge.

The following types of adhesives are used for bonding high density and medium density polyethylene:

- Two-component polyurethane or epoxy adhesives.
- Vinyl acetate copolymer hot melt adhesives.
- Dispersion or solvent-type pressure-sensitive adhesives.
- Polyurethane contact adhesives.

Reference: *Lupolen Polyethylene and Novolen Polypropylene Product Line, Properties, Processing*, Supplier design guide (B 579 e / 4.92), BASF Aktiengesellschaft, 1992.

BASF AG: Lupolen

Since Lupolen moldings are nonpolar and offer high resistance to solvents, very little scope exists for bonding them together with adhesives. However, if their surface tension has been increased by treatment with a flame or corona discharge, bonds with adhesives are feasible, provided that no high demands are imposed on their strength. Thus a suitable application is labeling.

Reference: *Lupolen, Lucalen Product Line, Properties, Processing*, Supplier design guide (B 581 e/(8127) 10.91), BASF Aktiengesellschaft, 1991.

30.1.9 Mechanical Fastening

BASF AG: Lupolen

If the necessary holes are drilled, Lupolen parts can be joined together by self-tapping screws. If the connections have to be loosened very often, preference should be given to threaded metal inserts, which can be firmly bonded to the Lupolen part by various means, e.g., encapsulation by molding, countersinking by force or ultrasonic techniques.

By virtue of their flexibility, Lupolen and Lucalen moldings can be firmly joined together by means of projections, beads, or hooks that fit into corresponding recesses. The size of the retaining angle, which may vary between 15° and 90°, determines whether the connections are permanent or can be easily loosened.

Reference: *Lupolen, Lucalen Product Line, Properties, Processing*, Supplier design guide (B 581 e/(8127) 10.91), BASF Aktiengesellschaft, 1991.

30.2 Low Density Polyethylene

30.2.1 General

BASF AG: Lupolen

The following methods of assembly may be adopted for Lupolen PE-LD moldings: welding, adhesives, snap-on connectors, and bolted connections.

Reference: *Lupolen, Lucalen Product Line, Properties, Processing*, Supplier design guide (B 581 e/(8127) 10.91), BASF Aktiengesellschaft, 1991.

30.2.2 Spin Welding

LDPE

In spin welding tests, braking with an abrupt stop always gave a higher weld quality than continuous braking. Weld quality initially increases with increasing friction time. Once Phase III (steady state friction phase) is reached, a longer friction time no longer gives increased strength. In the case of low density polyethylene it is the speed that has a decisive influence on seam quality. At speeds of 3 m/s (10 ft/s), a weld factor (strength of weld/strength of bulk material) of about 0.6 is achieved. Increasing the speed to 6 m/s (20 ft/s) increases the weld factor to values approaching 0.8.

Reference: Tappe P, Potente H: New findings in the spin welding of plastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

30.2.3 Heat Sealing

LDPE (form: film)

Process and film parameters affecting the peel strength of impulse heat sealed thermoplastic polymeric films were investigated, in particular, the roles of film thickness and duration/temperature of application of the impulse heat sealing tool. Trials were carried out using an impulse sealing unit with one nichrome wire strip, located in its stationary jaw, and covered by a Teflon coated fabric strip. The nichrome wire strip width was 1.1 mm (0.043 inches) and its sealing length was 469.9 mm (18.5 inches). Commercially available LDPE films used in bag manufacturing were obtained in thicknesses of 0.0254, 0.0381, 0.0508, 0.0762, 0.1016, and 0.1524 mm (0.001, 0.0015, 0.002, 0.003, 0.004, and 0.006 inches). The welds produced were subjected to a T-peel test.

As the weld time increased, the breaking load of the impulse seal steadily increased. This is due to the longer duration of electric current impulse and increased temperature at higher weld times. However, as the weld time increased to the limits of the impulse sealing apparatus, some film combinations began to show deterioration in breaking load. This occurred due to overheating and degradation of the LDPE films.

Although each family of LDPE film combinations tested had a slightly different optimal impulse sealing setting, it was observed on average that a duration of electric current of 1.3 seconds and a temperature at the top surface of the release film of 193°C (379°F) produced an impulse seal characterized by the highest possible breaking load, regardless of film thickness.

While most samples broke by cohesive failure, it was observed that the samples sealed at the lowest settings (115–125°C (239–257°F) and 0.5–0.7 seconds) broke via peeling at the interface of the two films at the site of the impulse seal. This trend is due to decreased melting at the interface of the two films during sealing and a weaker cohesive bond. These settings may be of interest for LDPE film applications in which a weak seal with good peelability is desired.

Reference: Raymond M, Leczynski A, Iovanna J, Tayebi A: Effect of impulse heat sealing process parameters on bond strength of low density polyethylene films. ANTEC 2005, Conference proceedings, Society of Plastics Engineers, Boston, May 2005.

Exxon: 105BR (features: blends with LLDPE, form: 25.4 μm (0.001 inch) thick blown film)

The constant heat and impulse heat sealing behavior of blends of LDPE, C4-LLDPE, C8-LLDPE, metallocenic LLDPE and polyethylene plastomers was investigated.

After a thorough analysis of experimental data, it can be concluded that the impulse heat sealing process is more sensitive to process parameters and configuration changes in sealing equipment than to film composition changes. It appears that the impulse heat sealing is more sensitive to the process parameters of voltage and time. Heat sealing behavior is also very sensitive to configuration parameters of sealing equipment, such as: electrical resistance and shape of the heat band; thickness and quality of the non-stick tape; and hardness of the rubber pad. It can also be concluded that in impulse heat sealing a very small difference in voltage (about 0.05V AC) makes the difference between a seal and no seal.

Sealing performance, particularly the constant heat sealing, can be correlated with DSC melting point. The seal initiation temperature is a value similar or some degrees above the ending temperature of the melting peak.

Reference: Sierra JD, Noriega MdP: Investigation of phenomenological differences of impulse heat sealing and constant heat sealing in Ziegler Natta and Metallocene polyolefin blends. ANTEC 2003, Conference proceedings, Society of Plastics Engineers, Nashville, May 2003.

Winzen International: Stratofilm 372
(form: 0.0008 inch (0.02 mm) thick blown film)

Samples were welded at temperatures between 100°C (212°F) and 200°C (392°F). Both room temperature and low temperature T-peel mechanical tests were performed in accordance with ASTM Method D882.

Samples with welds produced at 100°C (212°F) failed at much lower yield stress and % strain at break. The 100°C (212°F) welded samples were observed to undergo failure in the weld region; the failure mode is commonly known as “peel seal”. All other welded samples failed in a ductile fashion with deformation occurring throughout the length of the samples; failure did not occur at the weld.

All welded samples failed at approximately 300% strain during ambient temperature testing. In contrast, all welded samples failed at approximately 20% strain or less when tested at –80°C (–112°F). The brittle failures at –80°C (–112°F) all occurred in the parent film parallel with, and directly adjacent to, the weld.

At a test temperature of –60°C (–76°F) there was a clear correlation between the number of samples exhibiting brittle failures and the welding temperature.

The increase in both HAZ width and brittle failure rate with increasing temperature suggests the increasing size of the HAZ is the key factor in the increased brittle failures seen in the welded LDPE thin film systems studied here.

Reference: Weston TE, Harrison IR: The role of a heat affected zone (HAZ) on mechanical properties in thermally welded low density polyethylene blown film. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

30.2.4 Adhesive Bonding

Dow Chemical: 722M LDPE

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 30.2 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many

Table 30.2. Shear Strengths of Dow Chemical 722M LDPE to LDPE Adhesive Bonds made using Adhesives Available from Loctite Corporation*

Material Composition		**Loctite Adhesive**					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	5 rms	<50 (<0.3)	150 (1.0)	500 (3.5)	150 (1.0)	150 (1.0)	350 (2.4)
Roughened	88 rms	<50 (<0.3)	150 (1.0)	500 (3.5)	150 (1.0)	150 (1.0)	350 (2.4)
Antioxidant	0.1% Irganox 1010	50 (0.3)	150 (1.0)	500 (3.5)	150 (1.0)	150 (1.0)	350 (2.4)
UV stabilizer	0.3% Cyasorb UV-531	100 (0.7)	100 (0.7)	200 (1.4)	150 (1.0)	200 (1.4)	150 (1.0)
Flame retardant	16% DER-83R 6% Antimony Oxide	100 (0.7)	150 (1.0)	500 (3.5)	150 (1.0)	150 (1.0)	100 (0.7)
Lubricant	1% Synpro 114-36	100 (0.7)	150 (1.0)	500 (3.5)	150 (1.0)	150 (1.0)	350 (2.4)
Filler	17% OmyaCarb F	100 (0.7)	150 (1.0)	500 (3.5)	300 (2.1)	200 (1.4)	350 (2.4)
Colorant	0.1% Watchung Red B RT4280	<50 (<0.3)	100 (0.7)	500 (3.5)	50 (0.3)	150 (1.0)	100 (0.7)
Antistatic	0.4% Armostat 375	<50 (<0.3)	600 (4.1)	500 (3.5)	750 (5.2)	150 (1.0)	200 (1.4)

*All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 30.2 so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Loctite 3030 adhesive typically achieved bond strengths that were higher than the unfilled resin. Prism 401 instant adhesive, when used in conjunction with Prism Primer 770, achieved good bond strengths on this difficult-to-bond plastic. The addition of an antistatic agent significantly enhanced the bond strengths of Prism 401 and Super Bonder 414 instant adhesives.

Surface Treatments: Prism primer 770, when used in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused a statistically significant increase in the bond strengths achieved on all of the formulations of LDPE that were evaluated, with the exception of the formulation which contained an antistatic agent additive. Surface roughening caused no statistically significant effect on the bondability of LDPE.

Other Information: LDPE is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics*, *Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

30.3 High Density Polyethylene

30.3.1 Heated Tool Welding

HDPE (form: pipe)

The recommended socket fusion welding parameters for PE-HD pipes are given in Table 30.3.

The temperature of the heated tool should be 250–270°C (482–518°F).

Reference: Frank T: Heated tool welding of thermoplastic pipes (example polyolefins). AWS/DVS Conference on Plastics Welding, Orlando, October 2000.

HDPE (form: injection molded ISO type tensile test bar)

Hot plate temperatures were set at between 185°C (366°F) and 260°C (500°F). Heating times were varied from 10 seconds to 65 seconds, and the welding pressure was kept constant at 1.379×10^5 Pa (20 psi). During the welding process, the weld displacement was also recorded.

The maximum attainable joint strength was 100% of the bulk material strength. However, the energy at break was not proportional to joint strength. The results also showed that the samples having the joint strengths of 100% of the bulk material strength might not have the same energy at break.

A minimum melt layer thickness of 2.5 mm (0.098 inches) (both sides) was required to obtain a good joint quality. A minimum welding displacement of 0.75 mm (0.03 inches) (both sides) or a minimum squeeze-out ratio of 0.3 were required to produce a good quality joint.

Reference: Poopat B, Wu CY, Benatar A, Park JB: Optimization of contact hot plate welding of HDPE. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

HDPE

Results showed that, when either time or temperature are increased, the weld strength increased until a maximum is reached. This was at 100% of the normal sample strength for HDPE.

Table 30.3. Recommended Heating and Cooling Times for Socket Fusion Welding of PE-HD

Pipe Outside Diameter (inches)	Heating Time (s)		Maximum Change-over Time (s)	Cooling Time	
	SDR11	SDR17.6		Fixed (s)	Total (min)
3/8	5		4	6	2
½	5		4	6	2
¾	7		4	10	2
1	8		6	10	4
1¼	12		6	20	4
1½	12		6	20	4
2	24	10	8	30	6
2½	30	15	8	30	6
3	40	22	8	40	6
4	50	30	10	50	8
4½	60	35	10	60	8

SDR: Standard dimension ratio = outside diameter/wall thickness.

Reference: Rapai J: Tensile strength evaluation of hot plate welds in polypropylene and polyethylene. ANTEC 1997, Conference proceedings, Society of Plastics Engineers, Toronto, May 1997.

HDPE

The results of this study are summarized in Table 30.4 and indicate that weld joint strength in HDPE depends strongly on melt index. Lower melt index polymers with their higher heated tool melt viscosity are able to tolerate the use of higher platen temperatures which can generate a larger heat affected zone. This, in turn, permits the formation of a strong joint. For injection molding grade polyolefins, experience has been that across a broad range of process conditions, attainable weld strength is less for higher melt index materials. This is because their low melt viscosities pose a practical limit on how much heat can be applied to the weld joint without having melt beads stick to the heater platen. While better release coatings on the heater platen will mitigate the problem somewhat, the effect of melt viscosity on platen temperature selection limits the formation of the heat affected zone (consisting of melted or soft polymer) in high melt index HDPE polymers. It was observed that some of these materials did not reach the weld displacement stop setting of 0.03 cm (0.012 inches), indicating the presence of a cold seal where all molten material has been squeezed out of the joint. This results in a brittle weld joint that is easily broken.

Table 30.4 Tensile and Falling Dart Impact Results for Heated Tool Welded and Bulk Samples of Commercial High Density Polyethylene (HDPE) Polymers

Material					Falling dart impact for weld and bulk samples			Weld tensile results		
Supplier	Grade	Melt Index g/10 min	Density g/cc	Welding Temp. °C	Average Weld Impact Energy Nm (in. lb)	Average Bulk Impact Energy Nm (in. lb)	Weld Factor (Weld/Bulk)	Failures during Testing %	Average Stress @ Failure MPa (psi)	Average Strain @ Failure %
Quantum	LF6030	3.0	0.952	170				0		
Quantum	LF6040	5.5	0.962	160	24.6 (224)	33.0 (300)	0.75	50	26.1 (3792)	5.9
Quantum	LS5060	8.0	0.948	150	10.1 (92)	30.9 (281)	0.33	40	19.8 (2880)	10.2
Quantum	LS6060	10.0	0.962	140	12.1 (110)	33.0 (300)	0.37	100	17.1 (2480)	1.8
Quantum	LS6901	10.5	0.952	140	10.6 (96)	30.7 (279)	0.34	100	21.9 (3184)	5.5
Phillips	HMN 4550	5.0	0.945	160	27.3 (248)	35.1 (319)	0.78	80	19.1 (2768)	6.2
Phillips	HMN 6060	7.5	0.963	150				100	24.5 (3552)	5.4
Phillips	HMN 6060-01	4.0	0.963	170				40	24.6 (3568)	5.4
Mobil	HMA045	7.0	0.952	150	20.7 (188)	33.0 (300)	0.62	40	18.2 (2640)	16.0
Mobil	NRA235	5.0	0.937	170	23.1 (210)	38.1 (346)	0.61	20	14.3 (2080)	13.6
Mobil	HRA034	3.5	0.940	200				0		
Dow	12350N	12.0	0.950	140	9.9 (90)	37.2 (338)	0.27	100	19.3 (2800)	6.8
Exxon	LL6407	7.0	0.935	150	14.0 (127)	34.4 (313)	0.40	20	14.1 (2048)	9.7

Based on flex and tensile results, polymer density also affects weld strength. Results indicate that, for constant melt index, increasing the polymer density results in a higher percentage of tensile failures. To explain this effect, note that higher density polymers have a greater proportion of crystalline regions in their structure. Furthermore, in highly crystalline materials the melting temperature region is narrower than for polymers of lower crystallinity. Because of this phenomenon, in welding applications the heat affected zone is thinner for higher density HDPE materials than those of lower density. This leads to more brittle welds and as a result, attainable weld strength tends to be lower for high density polymers.

Reference: McGreevy RJ: Hot plate welding of high density polyethylene: the effect of melt index and density on weld strength. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

30.3.2 Ultrasonic Welding

HDPE (form: AWS ultrasonic test specimen)

Ultrasonic welding of four HDPE nanocomposites with 0, 3, 6 and 9 wt% nanoclay was investigated. The effect of weld force, amplitude of vibration and weld time for energy director joints or weld collapse for shear joints, on weld strength were evaluated. Three parameter, three level design of experiments were utilized to find near-optimum welding parameters.

For HDPE energy director samples, the maximum weld strengths were 21.54, 9.39, 7.65, and 6.23 MPa (3124, 1360, 1110, and 904 psi) for the 0, 3, 6, and 9 wt% nanoclay, respectively. This clearly shows that the maximum weld strength decreases with increasing nanoclay content. These samples had low weld strengths and this suggests that an energy director joint may not be the best option for welding nanocomposites.

For the shear joint samples, the maximum weld strengths were 25.42, 19.43, 19.01, and 16.45 MPa (3687, 2818, 2757 and 2386 psi) for the 0, 3, 6, and 9 wt% nanoclay, respectively. These were obtained using the following welding parameters: 24.7 μm peak-to-peak amplitude, 578.2 N (130 lbf) weld force and 0.381 mm (0.015 inches) weld collapse. It can be seen that the decrease in weld strength with increasing clay content was much lower for the shear joint samples, probably due to the more favorable flow of the melt compared to energy director joints. Shear joints also have the advantage that load transfer through the joint can be increased by increasing the collapse or weld area. Therefore, for ultrasonic welding of HDPE nanoclay composites, shear joints would be a better choice than energy director joints.

Reference: Flowers S, Humphrys S, Thomas J, Mokhtarzadeh A, Benatar A: Study of ultrasonic welding of HDPE-based nanoclay composites. ANTEC 2006, Conference proceedings, Society of Plastics Engineers, Charlotte, May 2006.

HDPE

The recommended near-field ultrasonic welding conditions for HDPE are:

- Amplitude of oscillations: 40 μm
- Frequency: 22 kHz
- Welding force: 500 N (112 lbf)
- Welding time: 1.2 seconds

Reference: Vinogradov AA: Selecting the method and conditions of welding components of low-pressure polyethylene. *Welding International*, 13(4), p. 413, 1999.

HDPE

Far field welding of high density polyethylene was not successful. The parts melted at the horn/part interface with little or no melting of the energy director. It is suggested that for semicrystalline polymers, the length of the part should be chosen such that the joint interface is at a displacement antinode. This is done by designing the top part to be half a wavelength. This will make far field ultrasonic welding as effective for semicrystalline polymers as it is for amorphous polymers.

Reference: Benatar A, Cheng Z: Far-field ultrasonic welding of thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

HDPE

Near field welding of high density polyethylene was successful, but amorphous materials produce stronger bonds. It was generally found that increasing the weld pressure initially increases the weld strength, with further increases in pressure decreasing strength due to unfavorable molecular alignment. Increasing the weld time increased energy dissipated and strength; the strength leveled off at weld times greater than 1.5 seconds. Increasing the amplitude of vibration increased the energy dissipated and strength more than with amorphous polymers such as ABS and polystyrene—with the exception of low amplitudes.

Reference: Benatar A, Eswaran RV: Near-field ultrasonic welding of thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

30.3.3 Spin Welding

HDPE

In spin welding tests, braking with an abrupt stop always gave a higher weld quality than continuous braking. Weld quality initially increases with increasing friction time. Once Phase III (steady state friction phase) is reached, a longer friction time no longer gives increased strength. In the case of high density polyethylene it is the speed that has a decisive influence on seam quality. At speeds in excess of 3 m/s (10 ft/s), a weld factor (strength of weld/strength of bulk material) approaching 1 is achieved.

Reference: Tappe P, Potente H: New findings in the spin welding of plastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

30.3.4 Radio Frequency Welding

HDPE

Radio frequency heating has traditionally been used for sealing thin films, such as PVC, or in the volumetric heating of bulk materials. This is the first study that shows that HDPE parts can be joined using a conductive polymer gasket and radio frequency heating. The gasket is made of a conductive polymeric composite of polyaniline and high density polyethylene. It is placed at the joint of HDPE parts and selectively heated using radio frequency energy at 27.12 MHz. Joint strengths as high as the bulk material were achieved.

Reference: Faisst CF, Benatar A: A feasibility study of radio frequency joining of HDPE using conductive polymeric composite. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

30.3.5 Hot Gas Welding

HDPE (form: sheet)

The following welding conditions are recommended for HDPE: temperature of 300–350°C (572–662°F), force (for a 4 mm (0.16 inch) diameter welding rod) of 25–35 N (5.6–7.9 lbf) and a gas flow of 40–60 l/minute.

Reference: Gibbesch B: Thermoplastic inliner for dual laminate constructions. Welding Beyond Metal: AWS/DVS Conference on Plastics Welding, New Orleans, March 2002.

30.3.6 Extrusion Welding

HDPE (form: sheet)

On the basis of the results of the tests made on 10 mm (0.39 inch) and 20 mm (0.79 inch) thick butt joints and T joints, as well as carrying out an investigation into the mechanical properties of such joints, the optimal parameters for the extrusion welding of HDPE are: a plasticizing temperature for the filler material of 220°C (428°F), an air temperature for the plasticization of the weld groove of 250–275°C (482–527°F), and a feed rate of 3 mm (0.12 inch) diameter filler rod of 222–335 cm/minute (7.28–11.00 ft/minute).

To produce satisfactory joints, bevelling of the sheet to be welded is necessary and should be carried out in such a way that the angle of the welding groove is 90°. The shape and dimensions of the forming overlay should be compatible with those of the welding groove.

Reference: Dziuba S, Boron S: The technology of extrusion-fusion welding of polythene and polypropylene butt and T joints. *Welding International*, 14(9), p.677, 2000.

30.3.7 Laser Welding

HDPE

Transmittance and reflectance of HDPE were measured for various thicknesses and incident angles of the laser beam (from a 50 W diode laser with a wavelength of 810 ± 10 nm). Transmittance decreased rapidly with increasing thickness due to dispersion effects from the spherulite structure. Reflectance did not depend on the material thickness but it increased as the incident beam angle increased.

Reference: Rhew M, Mokhtarzadeh A, Benatar A: Diode laser characterization and measurement of optical properties of polycarbonate and high-density polyethylene. ANTEC 2003, Conference proceedings, Society of Plastics Engineers, Nashville, May 2003.

HDPE (form: 3.42 mm (0.13 inch) thick extruded sheet)

A T-sample was used where both the flange (20 × 12.7 × 3.42 mm; 0.79 × 0.5 × 0.13 inches) and tee/top (20 × 63.3 × 3.42 mm; 0.79 × 2.5 × 0.13 inches) components were machined from natural and unfilled HDPE sheet. To promote laser absorption at the interface, a black HDPE film (20 × 7 × 0.13 mm; 0.79 × 0.28 × 0.005 inches, with 5% carbon black) was placed at the faying surface.

Increasing the power at the weld interface from 0.31 to 0.47 W resulted in substantial melting at the base of the tee. This increased the size of the fillet that formed at the base of the weld, resulting in increasing joint strength, to around 95% of parent material strength.

Reference: Rhew M, Mokhtarzadeh A, Benatar A: Through transmission laser welding of polycarbonate and high-density polyethylene. ANTEC 2003, Conference proceedings, Society of Plastics Engineers, Nashville, May 2003.

HDPE (form: sheet)

It is possible to produce high quality joints in high density polyethylene, naturally colored, sheets by butt welding with a diode laser at powers between 100 and 200 W. The required level of energy is very much lower than that needed, for instance, for hot plate welding. Butt joints in 2.0 and 4.0 mm (0.079 and 0.16 inch) thick, naturally colored PE-HD welded within the optimal parameter range possessed mechanical properties that were not lower than those of the parent material. The beam energy and the rate of welding had the most noticeable effect on the joint quality. Focusing of the 2.2 × 7.1 mm (0.087 × 0.28 inch) laser beam on the upper surface of the joint enabled the optimal bead shape to be produced.

Reference: Klimpel A, Lisiecki A, Oledzki A: Diode-laser butt welding of thermoplastic sheet. *Welding International*, 16(11), p.845, 2002.

HDPE (form: AWS ultrasonic test specimen)

To investigate the efficiency of the laser transmission welding process, an Nd:YAG laser was used. The maximum power incident on the laser-transparent joint part was 40 W. The beam diameter for all experiments corresponded to the wall thicknesses of the joint parts of 2.5 mm (0.1 inches), and a constant joint pressure of 0.3 N/mm^2 (44 psi) was used. The other welding parameters used are given in Table 30.5.

Table 30.5. Parameters for Laser Welding of HDPE

Carbon Black Content (wt%)	No. of Scans	Scan Velocity (mm/s)	Short-Term Welding Factor
0.05	1	3.4	0.85
0.05	2	7.5	1
0.3	1	7.5	0.6
0.3	2	5.5	0.86

As can be seen from Table 30.5, a second scanning of the joint zone has a positive effect on the seam quality; during the first scan, optimum thermal contact is achieved between the joint parts, whereas during the second scan the welding itself occurs.

Reference: Potente H, Korte J, Stutz R: Laser-transmission welding of PE-HD. *Kunststoffe*, 87(3), p. 348, 1997.

HDPE

Under optimum welding conditions, laser welding of high density polyethylene produces joints with strengths (27.4 ± 1.3 MPa (3970 ± 190 psi)) and elongations equal to the bulk material. In those cases, failure usually occurred outside the weld region. Among the welding parameters studied (power, beam offset from the focal point being on the tip surface of the specimen, shielding gas flow rate, welding pressure, and travel speed), laser beam offset (power density) and welding pressure showed the most significant effect on the joint strength. Increasing beam offset while decreasing power density increased the joint strength all the way to the highest offset tested. For HDPE there existed an optimum pressure for achieving the highest joint strength. The effect of power, travel speed and shielding gas flow rate on joint strength was very small as long as the interface could be cut in one pass. Generally, laser welding of HDPE was very fast and required no pre-welding preparations.

Reference: Ou B S, Benatar A, Albright CW: Laser welding of polyethylene and polypropylene plates. ANTEC 1992, Conference proceedings, Society of Plastics Engineers, Detroit, May 1992.

30.3.8 Infrared Welding

HDPE (form: injection molded ISO type tensile test bar, 4 mm (0.16 inches) thick)

For non-contact hot plate welding, the hot plate temperature was set at 371°C (700°F) and 427°C

(800°F). The non-contact gap was kept constant at 1 mm (0.04 inches). Heating times were varied from 10 to 65 seconds. Welding pressure was set at 138 kPa (20 psi) and 206 kPa (30 psi). The weld displacement was recorded by measuring the total reduction in length of the samples after welding. Reduced welding parameters of melt layer thickness, weld displacement and the ratio of weld displacement to melt layer thickness were used as control parameters in the optimization process.

A linear relationship between the melt layer thickness and the product of the hot plate temperature and square root of time was found. The y-intercept depended on the heating conditions and was a function of the hot plate temperature, the non-contact gap and the thermal diffusivity of air.

The maximum attainable joint strength was equal to the bulk strength of HDPE. The optimum melt layer thickness was 3.5 mm (0.14 inches) (both sides) and the optimum displacement-melt ratio was about 0.75.

Using a very high hot plate temperature can result in degradation of the material at the joint, thereby producing welds with low energy at break. Therefore, high welding pressure is necessary to squeeze out as much of the degraded material as possible.

Reference: Poopat B, Benatar A, Park JB: Comparative study of contact and non-contact hot plate welding of HDPE. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

30.3.9 Induction Welding

HDPE

Figure 30.1 is an example of welding 50 mm (1.97 inch) threaded HDPE fittings directly to the opening of 95, 114, and 209 liter blow-molded drums. For reconditioning drums, the fitting can be removed if previously damaged and replaced with a new fitting.

Reference: Chookazian SM: Electromagnetic welding of thermoplastics and specific design criteria with emphasis on polypropylene. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

30.3.10 Friction Stir Welding

HDPE

Friction stir welding of HDPE has been demonstrated to be a viable joining process, with tensile strengths of 95% of the base material strength.

A special tool with a fixed shoe, rather than a rotating shoulder, is necessary to successfully weld thermoplastics. The shoe should have a controllable temperature to optimize the FSW process. Tools with smooth pins are unacceptable threaded tools with both straight and tapered pins appear to work well.

The machine spindle speed appears to be the most significant process parameter for FSW of thermoplastics.

Reference: Sorensen CD, Nelson TW, Strand S, Johns C, Christensen J: Joining of thermoplastics with friction stir welding. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

30.3.11 Microwave Welding

HDPE

The conductive polymer used throughout this work was polyaniline (PANI) doped with HCl. In order to assure structural compatibility at the interface, PANI

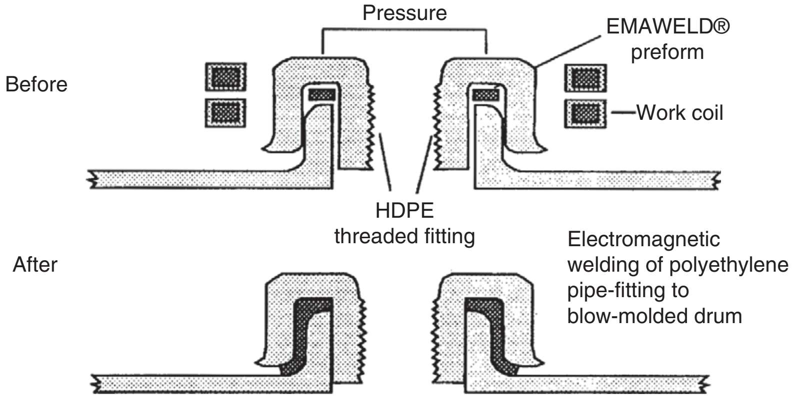


Figure 30.1. Blow-molded 114 liter drum with HDPE fitting assembled using electromagnetic welding.

and HDPE powder were initially mixed and a gasket was compression molded. The resulting heat in the gasket is conducted into the samples, generating a molten layer. Pressure is applied to ensure adequate surface contact.

An optimization of the welding parameters was first performed, followed by a study of the disassembly capacity. The welding parameters taken into consideration were the percentage of conductive polymer (30, 40, 50 and 60% by weight), microwave power (2400, 1800, 1200 and 600 W) and heating time. The welding pressure was maintained constant at 0.69 MPa (100 psi).

Both untuned and tuned microwave systems were used to study the disassembly capacity. The total displacement was used as a single parameter to characterize the welding and disassembly process. If the total displacement was at least 2.7 mm (0.106 inches), then the achieved joint strength was at least 90% of the bulk strength. A joint with a tensile strength of approximately 60% of the bulk strength can be disassembled in an untuned microwave system with a relatively low force of 27 N (6.1 lbf). However, a long reheating time of 120 seconds and a high power level of 2000 W is needed for disassembly to occur. For a tuned single-mode microwave system, while the reheating time and power level decreased to 30 seconds and 1000 W, respectively, the maximum joint strength that can be disassembled increased to 80% of the bulk strength. The maximum displacement that can be disassembled is 1 mm (0.04 inches), regardless of the concentration of PANI used. After disassembly, the 60% samples were welded once more with the same parameters as the original welds. Tensile testing performed on the rewelded sample showed a maximum loss of 15%.

Reference: Staicovici S, Wu CY, Benatar A: Welding and disassembly of microwave welded HDPE bars. ANTEC 1997, Conference proceedings, Society of Plastics Engineers, Toronto, May 1997.

HDPE

In this study a new 3000 W microwave system operating at 2450 MHz, which provides a more stable and narrower band signal, was used. Also, an impedance matching technique was used to improve the energy transfer efficiency, which reduces the input power dramatically. In welding experiments, two different composite heating elements were made, one with a mixture of 10% HCl-doped polyaniline powder and 90% HDPE powder and another with Versicon (a commercial polyaniline from Allied Signal) and HDPE in the range of 5–10% loading.

Results showed that the Versicon conductive polymer heats up faster than HCl-doped polyaniline at the microwave frequency, which reduces the welding time and concentration in the heating composite dramatically. The temperature increase at the joint interface depends on the power used in welding, a higher power input results in a higher interface temperature. Use of 10% Versicon in welding with 750 W power resulted in 96% of the joint strength in 25 seconds. Use of 5% Versicon heating composite results in 90% of the joint strength in 40 seconds. Use of HCl-doped polyaniline powder results in 80% of the joint strength in 50 seconds. It is concluded that Versicon has higher microwave absorption than HCl-doped polyaniline.

Reference: Wu CY, Staicovici S, Benatar A: Microwave welding of HDPE using impedance matching system. ANTEC 1997, Conference proceedings, Society of Plastics Engineers, Toronto, May 1997.

HDPE

Intrinsically conductive polyaniline (PANI) composite gaskets were used to microwave weld high density polyethylene (HDPE) bars. Two composite gaskets were made from a mixture of HDPE and PANI powders in different proportions.

It was found that increasing the heating time and the welding pressure increased the joint strength. The maximum tensile joint strength was achieved using a 60 wt% PANI gasket with a heating time of 60 seconds and a welding pressure of 0.9 MPa (130 psi); this resulted in a tensile weld strength of 24.79 ± 0.34 MPa (3595 ± 49 psi), which equals the tensile strength of the bulk HDPE.

Reference: Wu CY, Benatar A: Microwave welding of high density polyethylene using intrinsically conductive polyaniline. *Polymer Engineering and Science*, 37(4), p.738, 1997.

HDPE

Welding of HDPE using conductive polyaniline and a single mode microwave system was investigated. The orientation and the position of the heating element inside the waveguide determine the electromagnetic absorption of the gasket during welding. This affects the time needed to create the molten layer which controls the length of the welding cycle. The best position for gasket location was measured to be at 3.7 cm (1.46 inches) from the shorted end (reflection plate). The gasket must be parallel to the electric field to have the best heating results. Power level is another factor dictating the cycle time. High power level reduces the cycle time dramatically. Considering the joint strength and cycle time, the best joining condition using 2400 W and 0.69 MPa (100 psi) cooling pressure is probably about 15 seconds. Further improvements can be made by increasing the welding pressure and/or power level.

Reference: Wu CY, Benatar A: Single mode microwave welding of HDPE using conductive polyaniline/HDPE composites. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

HDPE

A novel technique for joining high density polyethylene using microwaves was developed. Polyaniline, a conductive polymer, was synthesized and three types of composite gaskets were made by compression molding. Microwave conductivity at 8.976 GHz was 0.023 S/cm for the 50% PANI gasket and 0.067 S/cm for the 60% PANI gasket. The loss tangent at 8.976 GHz was 0.4 for the 50% PANI gasket and 0.5 for the 60% PANI gasket. Welding of HDPE was done by placing these gaskets at the joint interface. Longer welding times resulted in stronger joints. The higher the % PANI in the gasket, the faster the welds were made and the stronger the welds became. The joint strength using a 60% PANI gasket with a weld time of 120 seconds and a pressure of 0.3 MPa (43 psi) was 19.43 ± 0.77 MPa (2818 ± 111 psi), which was 86% of the strength of the molded HDPE bar. For a 1 mm (0.04 inch) thick gasket with 50% PANI, the joint strength for a weld time of 80 seconds and a pressure of 0.3 MPa (43 psi) was 19.42 ± 0.47 MPa (2816 ± 68 psi) which was also 86% of the strength of the molded HDPE bar. Doubling the pressure increases the joint strength. To achieve the maximum joint strength, one should squeeze out most of the gasket from the interface.

Reference: Wu CY, Benatar A: Microwave joining of HDPE using conductive polymeric composites. ANTEC 1992, Conference proceedings, Society of Plastics Engineers, Detroit, May 1992.

30.3.12 Adhesive Bonding

Compression Polymers: HDPE

A study was conducted to determine the bond strength of high density polyethylene and the adhesives best suited to it. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad.

While the bond strengths in Table 30.6 give a good indication of the typical bond strengths that can be achieved they also face several limitations. For example, a consideration that must be kept in mind when using this data to select a suitable adhesive is how well the block shear test method will reflect the stresses that

Table 30.6. Shear Strengths of HDPE to HDPE Adhesive Bonds Made Using Adhesives Available from Loctite Corporation*

Plastic Material Composition		Loctite Adhesive					
		Black Max 380 (Rubber Toughened Cyanoacrylate (200 cP))	**Prism 401** (Surface Insensitive Ethyl cyanoacrylate (100 cP))	**Prism 401/ Prism Primer 770** (Polyolefin Primer for Cyanoacrylate)	**Super Bonder 414** (General purpose, cyanoacrylate (110 cP))	**Depend 330** (Two-Part, No-mix, acrylic)	**Loctite 3105** (Light Cure Acrylic (300 cP))
High density polyethylene	Courtesy of Compression Polymers	<50 (<0.3)	50 (0.3)	2000 (13.8)	50 (0.3)	150 (1.0)	100 (0.7)

*All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Prism 401 instant adhesive, when used in conjunction with Prism Primer 770, or Prism 4011 medical device instant adhesive with Prism Primer 7701, achieved the highest bond strengths on HDPE. All other adhesives tested with HDPE achieved low bond strengths. Polyethylene is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

30.4 Medium Density Polyethylene

30.4.1 Heated Tool Welding

DuPont: Aldyl (form: pipe)

Welds made using standard (material manufacturer recommendations) and non-standard (to study the effect of increased plate removal time) conditions could be distinguished in terms of structural and morphological behavior, but not always on the basis of tensile strength (Table 30.7). Poor tensile strengths were associated with the lack of a region of deformed spherulites at the weld/pipe interface, a wide weld, and a reduced amount of flow in the direction of the weld. Welding slightly decreases the crystallinity in the polyethylene welds. Welding reduced the amount of crystalline phase orientation parallel to the pipe axis.

Transmitted light microscopy did not always show morphological changes which were revealed by scanning electron microscopy (SEM) examination of etched samples such as the extent of heat affected zones (HAZ), or by Fourier Transform Infrared Spectroscopy (FTIR) such as annealed regions. The mode of etching (acid and solvent) involved the removal of disordered material between the lamellae and at the spherulitic boundaries.

Reference: Stevens SM: Structure evaluation of polyethylene and polypropylene hot plate welds. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

MDPE (form: pipe)

High-speed tensile tests and Charpy impact tests were conducted on fusion-joined pipe specimens to evaluate the short-term performance of fusion butt joints. Fatigue tests were carried out to evaluate the long-term performance of fusion joints. The changes in impact strength of fusion joints obtained by varying the heating conditions and material combination were discussed. The degree of crystallinity and orientation of fusion zones are different from those of the pipe substrate. As a result, joints subjected to rapid loadings do not seem to be able to undergo significant plastic deformation before fracture. The reduction in impact strength of fusion joints was larger than that of the substrate.

The reduction in impact strength and the strength of fused joints depends on the resin grade. The joint strength of PE having a high molecular weight was greatly reduced. This reduction may be caused by the weak flow of the molten resin at the fusion interface. It was shown that the fusion strength is affected by the

Table 30.7. Welding Details and Tensile Results for Hot Plate Welded Medium Density Polyethylene Pipes

Weld	Material	Total Heating Time, s	Plate Temperature, °C (°F)	Heating/ Welding Pressure, MPa (psi)	Plate removal time, s	Tensile Strength, MPa (psi)
Weld 1	Polyethylene	45	205 (401)	0.25 (36)	2	15.7 (2280)
Weld 2	Polyethylene	45	205 (401)	0.25 (36)	20	11.1 (1610)
Weld 3	Polyethylene	45	205 (401)	0.25 (36)	20	2.3 (330)
Parent material	Polyethylene					14.8 (2150)

heating conditions. For PE resin, with 0.935 g/cc density and 0.21 g/10 minute melt flow rate, impact strength decreased when the heating temperature was below 179°C (354°F) and/or the heating time was less than 30 seconds, and/or the applied pressure exceeded a certain value.

Reference: Narisawa I, Nishimura H: Short- and long-term properties of fusion-jointed polyethylene. ANTEC 1993, Conference proceedings, Society of Plastics Engineers, New Orleans, May 1993.

30.5 Linear Low Density Polyethylene

30.5.1 Heat Sealing

Eleme Petrochemical: Elpene

Heat sealing propertiehes of LLDPE blends with varying proportions of HDPE (Elpene F6A from Eleme Petrochemical) was investigated. LLDPE/HDPE binary blends of 20, 35 and 50% HDPE were produced. Sealing was carried out at a temperature range of 110–150°C (230–302°F). The peel test was used to determine the heat seal strength.

There was an observed linear increase in the seal temperature at which the highest value of seal strength was observed for the 20, 35 and 50% HDPE content blends at 125°C (257°F), 130°C (266°F) and 140°C (284°F), respectively. The 100% LLDPE attained maximal seal strength at 120°C (248°F). On attaining their maximum seal strength at the corresponding seal temperatures, the seal strength for the blends decreased with increasing seal temperature.

The heat sealing properties of LLDPE/HDPE binary blends are considerably enhanced by the HDPE content up to 35%.

Reference: Iwu CF, Egbuhuzor OM: HDPE effects on the heat sealing properties of LLDPE. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

Polinter: Resilin 11Q4 (features: butene LLDPE, blends with LDPE; form: 25.4 μm (0.001 inch) thick blown film); **Dow Plastics: Dowlex NG 2085** (features: octene LLDPE, blends with LDPE; form: 25.4 μm (0.001 inch) thick blown film); **Dow Plastics: Elite 5401** (features: metallocene LLDPE, blends with LDPE; form: 25.4 μm (0.001 inch) thick blown film)

The constant heat and impulse heat sealing behavior of blends of LDPE, C4-LLDPE, C8-LLDPE, metallocenic LLDPE and polyethylene plastomers was investigated.

After a thorough analysis of experimental data, it can be concluded that the impulse heat sealing process is more sensitive to process parameters and configuration changes in sealing equipment than to film composition changes. It appears that the impulse heat sealing is more sensitive to the process parameters of voltage and time. Heat sealing behavior is also very sensitive to configuration parameters of sealing equipment, such as: electrical resistance and shape of the heat band; thickness and quality of the non-stick tape; and hardness of the rubber pad. It can also be concluded that in impulse heat sealing a very small difference in voltage (about 0.05V AC) makes the difference between a seal and no seal.

Sealing performance, particularly the constant heat sealing, can be correlated with DSC melting point. The seal initiation temperature is a value similar or some degrees above the ending temperature of the melting peak.

Reference: Sierra JD, Noriega MdP: Investigation of phenomenological differences of impulse heat sealing and constant heat sealing in Ziegler Natta and Metallocene polyolefin blends. ANTEC 2003, Conference proceedings, Society of Plastics Engineers, Nashville, May 2003.

BP Chemicals: LLDPE (form: 40 μm (0.0016 inch) thick blown film)

The effect of heat sealing variables (platen temperature and dwell time) on seal strength of a linear low density polyethylene (LLDPE) was examined. In order to characterize the development of interfacial strength, blown films were heat sealed for times from 1 to 100,000 seconds, much longer than the typical sealing times of less than 1 second. The seal temperature ranged from 100–130°C (212–266°F).

From the differential scanning calorimetry thermogram, the LLDPE was determined to be completely melted at 130°C (266°F). Therefore, the films ranged from partially to fully melted when they were heat sealed. The seal strength was measured in the T-peel configuration, and the peel fracture surfaces were examined in the scanning electron microscope.

A temperature of 115°C (239°F) or higher was required to form a good seal. The strong effect of seal temperature was related to the heterogeneous composition of the LLDPE studied. At 115°C (239°F), the lower molecular weight, more highly branched chains easily diffused across the interface. Crystallization upon cooling produced connections across the interface. However, because these chains represented a small fraction of the crystallinity and the molecular weight was low, they contributed much less than the full peel strength. Conversely, chains with less branching represented the main fraction of crystallinity (anchors for tie chains) and the highest molecular weights (more entanglements). Only at temperatures at which the higher molecular weight, less branched chains began to melt and diffuse across the interface could high peel strengths be achieved.

Reference: Mueller C, Capaccio G, Hiltner A, Baer E: Heat sealing of LLDPE: relationships to melting and interdiffusion. *Journal of Applied Polymer Science*, 70, p. 2021, 1998.

30.6 Cross-linked Polyethylene

30.6.1 Heated Tool Welding

PEX (form: pipe)

For butt welding of PE-Xa (peroxide cross-linked) to PE-HD pipes, internal stresses caused during manufacture are released when the pipe ends are heated and this can cause problems for the butt welding of PE-X pipes. The dip of the pipe ends leads to a circular groove at the joint, which has a negative effect on long-term durability. This can be improved through repeated heating and then planing and cleaning the areas to be fused. If these effects are minimized, short-term welding factors of PE-Xa and PE-HD joints do achieve values that are comparable with PE-HD/PE-HD joints (welding factor of 0.9–1.0). The long-term characteristics of PE-X/PE-HD butt weld joints are not, however, anywhere near as good as those of pure PE butt welds. The best results are achieved with standard PE weld parameters. Temperatures at the heating element are between 200 and 220°C (392 and 428°F), joining pressures are 0.10–0.15 MPa (15–22 psi).

For butt welding of PE-Xa and PE-Xb (silicon hydride cross-linked) pipes to themselves, the standard butt welding methods for PE yield poor results.

Reference: Eckert R: Joining of PE-X pipes. Plastics Pipes XI, Conference proceedings, Munich, Germany, September 2001.

PEX (form: 100 mm (3.94 inch diameter pipe)

Butt fusion welding of two types of PEX pipe, cross-linked using peroxide (PEXa) and silane (PEXb), has been investigated.

Results showed that butt welding of fully cross-linked PEXb pipe (77% gel content) was unsuccessful. Butt welding of non-cross-linked PEXb pipe followed by cross-linking in hot water at 95°C (203°F) leads to strong welds, even at 158°C (316°F). The strength of such welds originates from the fact that the weld plane itself has become cross-linked as well.

Butt welding of fully cross-linked PEXa pipe leads to better results than butt welding of fully cross-linked PEXb pipes.

Reference: Scholten FL, Wolters M: Butt welding of PE and PEX pipes with small or no beads. 16th International Plastic Pipe Fuel Gas Symposium, New Orleans, November 1999.

PEX (form: pipe)

An investigation has been carried out into butt welding of peroxide cross-linked polyethylene.

Results showed that a degree of cross-linking between 70 and 90% does not affect the weld quality of peroxide cross-linked polyethylene (PEXa) foils and the residue of uncross-linked chains is not necessary for good weld strength. Butt welding of PEXa pipes to medium density polyethylene pipes is difficult, not because of fundamental problems with welding of PEXa, but due to the release of extrusion stresses, which cause deformation of the pipe wall at the molten ends.

Reference: Scholten L, Wolters M: Welding of peroxide, silane, and electron beam crosslinked polyethylene pipes. *Plastics, Rubber and Composites Processing and Applications*, 27(10), p. 465, 1998.

30.6.2 Resistive Implant Welding

PEX (form: pipe)

An investigation has been carried out into electrofusion welding of cross-linked polyethylene pipes, which had been cross-linked using the peroxide (PEXa), silane (PEXb) and electron beam (PEXc) processes.

Results showed that electrofusion welding of PEXa pipes provides good results, but electrofusion welding of silane and electron beam cross-linked polyethylene does not, probably owing to residues of the cross-linking process and polar additives, respectively.

Reference: Scholten FL, Wolters M: Welding of peroxide, silane, and electron beam crosslinked polyethylene pipes. *Plastics, Rubber and Composites Processing and Applications*, 27(10), p. 465, 1998.

30.7 Ultrahigh Molecular Weight Polyethylene

30.7.1 Heated Tool Welding

Cadillac Plastic and Chemical Company: Cadco

In butt welding (heated tool welding), both surfaces of the Cadco UHMWPE are held against a Teflon-coated tool. This tool is heated electrically with a rheostat to control the tool's temperature. As the surfaces of the two parts of Cadco UHMWPE turn clear and plastic, the tool is then removed and the parts pushed together with about 1 MPa (150 psi) and allowed to cool under pressure.

Reference: *Cadco Engineering Plastics*, Supplier design guide (CP-200-92), Cadillac Plastic and Chemical Company, 1992.

Hoechst AG: Hostalen GUR

In butt welding, the cleaned joint faces are held under slight contact pressure against the heated tool at 200°C (392°F) until on both sides a layer of about 4 mm (0.16 inches) deep has become plastic. The two parts are then pressed together under a contact pressure of 10–20 bar (1–2 MPa; 145–290 psi) depending on the material thickness until cold. If the material is greater in thickness than 30 mm (1.18 inches), contact pressures of 50 bar (5 MPa; 725 psi) and above are required and in such cases presses or special welding jigs are frequently used.

Reference: *Hoechst Plastics Hostalen GUR*, Supplier design guide (HKR112E8102/14), Hoechst AG.

30.7.2 Spin Welding

Cadillac Plastic and Chemical Company: Cadco

It is possible to achieve weld strengths of 94% using spin welding. Surfaces should be absolutely clean and parallel to achieve maximum strength.

Reference: *Cadco Engineering Plastics*, Supplier design guide (CP-200-92), Cadillac Plastic and Chemical Company, 1992.

30.7.3 Hot Gas Welding

Cadillac Plastic and Chemical Company: Cadco

Cadco UHMWPE can be welded with a low or high density polyethylene welding rod although the weld is not considered structural. It may nevertheless provide a good waterproof joint.

Reference: *Cadco Engineering Plastics*, Supplier design guide (CP-200-92), Cadillac Plastic and Chemical Company, 1992.

30.7.4 Friction Stir Welding

UHMWPE

Friction stir welding of UHMWPE has been demonstrated to be a viable joining process, with tensile strengths of 69% of the base material strength.

A special tool with a fixed shoe, rather than a rotating shoulder, is necessary to successfully weld thermoplastics. The shoe should have a controllable temperature to optimize the FSW process. Tools with smooth pins are unacceptable. Threaded tools with both straight and tapered pins appear to work well.

The machine spindle speed appears to be the most significant process parameter for FSW of thermoplastics.

Reference: Sorensen CD, Nelson TW, Strand S, Johns C, Christensen J: Joining of thermoplastics with friction stir welding. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

30.7.5 Adhesive Bonding

Hoechst AG: Hostalen GUR

The high solvent resistance of Hostalen GUR restricts the range of suitable bonding agents and two-component adhesives, and with these only moderate joint strength values are obtainable. An improvement in adhesion can be obtained by pretreating the Hostalen GUR surface. The usual methods are pretreatment with chromosulfuric acid, flaming with an oxidizing flame or an electrical method (spray discharge). Suitable equipment of various types for these methods is available.

Reference: *Hoechst Plastics Hostalen GUR*, Supplier design guide (HKR112E8102/14), Hoechst AG.

30.7.6 Mechanical Fastening

Cadillac Plastic and Chemical Company: Cadco

Plug welding is to be used in areas where it is undesirable or impossible to fasten Cadco UHMWPE sheeting by drilling holes through the existing substrate or support. This can be accomplished by drilling the Cadco UHMWPE and leaving a 4.8 mm (0.1875 inch) shoulder of Cadco UHMWPE at the bottom of the sheeting.

A metal welding grommet is then inserted into the hole. The welding rod tip is guided into the pilot hole in the metal plug and tacked in place to the metal substrate. Precut plugs of Cadco UHMWPE are inserted over the metal plug and driven flush to the surface of the Cadco UHMWPE sheeting. Sheets thinner than 6.4 mm (0.25 inches) should not be used.

Fasteners should be inserted no further than 51 mm (2 inches) from the borders of the Cadco UHMWPE sheeting. In addition, sheeting of less than 6.4 mm (0.25 inches) should not be used with mechanical fasteners. Test data also show that a 50% increase in holding power results from increasing the thickness of Cadco UHMWPE sheeting from 6.4 to 9.5 mm (0.25–0.375 inches). Further studies show that you can get an increase of 200% with a mechanical fastener by using 12.7 mm (0.5 inch) thick sheeting as opposed to 9.5 mm (0.375 inches).

Elevator bolts are used extensively in the grain industry as a reliable method of fastening Cadco UHMWPE to supporting surfaces. Maintenance engineers in all types of industries have made elevator bolts their first choice in fasteners because they can achieve maximum holding power and because of the ease in installing and removing the bolts when replacing a Cadco UHMWPE liner. Elevator bolts capped with UHMWPE are available for liners 6.4–25.4 mm (0.25–1.0 inches) thick. Capped bolts provide a continuous, smooth UHMWPE surface to eliminate material hang-up around the fastener area.

Note: Countersinking the heads flush with the Cadco UHMWPE surface is recommended because enlarged drill holes in the substrate or the liner will allow for expansion and contraction. Torquing the liner prevents expansion and contraction and can cause buckling.

The most versatile, fast and safe fastening method uses powder actuated fasteners. The tool uses 25 and 27 caliber powder charges to drive the fastener through the Cadco UHMWPE, and into the substrate. This fastening system can be used on concrete and steel substrates effectively. Expansion, contraction or vibration of the liner has a tendency to loosen nail-type fasteners in some substrates.

Note: When fastening Cadco UHMWPE to a steel substrate use 31.75–38.1 mm (1.25–1.5 inch) studs, R23 washer and red charge to power gun.

Screws: Stainless steel flat head screws are easy and economically available to use, although they are limited to use with such substrates as wood, concrete, masonry and plastic. The flat head screw should be anchored flush with the surface of the Cadco UHMWPE in order to prevent turbulence of the material being conveyed.

Note: Use this type of fastener with thicker sheets of Cadco UHMWPE only. Gauges of 9.5 mm (0.375 inches) and greater are suggested when using flat head screws. If there is an extreme change in temperature from the time of installation, material can expand and pull over the head of a flat head screw.

Reference: *Cadco Engineering Plastics*, Supplier design guide (CP-200-92), Cadillac Plastic and Chemical Company, 1992.

Hoechst AG: Hostalen GUR

Tapping and Self-tapping Screws: Threads can be cut in Hostalen GUR semi-finished product with normal metal cutting tools, either on a lathe (recommended speed 20–30 minute^{-1}) or by hand. In principle, round threads in accordance with DIN 405 are preferred, but V-threads still possess adequate strength properties because of the high notched impact strength of the material.

Reference: *Hoechst Plastics Hostalen GUR*, Supplier design guide (HKR112E8102/14), Hoechst AG.

30.8 Ethylene-Vinyl Acetate

30.8.1 Radio Frequency Welding

ExxonMobil Chemical: EVA

In thin (0.005 inch; 0.13 mm) film, slip agents have no effect on seal strength at concentrations from 0 to 3000 ppm, in that the slip agent is melted and flows out of the seal area and thus does not interfere with the diffusion for sealing. However, in thicker (0.015 inch; 0.38mm) film, slip agents appear to enhance seal strength. This results from the polar nature of slip molecules. As the film thickness increases, the number of slip molecules increases, leading to more rapid heat generation at the interface, which facilitates melting and sealing.

Antiblock agents have a major impact on seal strength. Apparently, heat generation is enhanced by the presence of silica. The effect is to double the seal strength of EVA when 7000 ppm antiblock is added.

Reference: *Tip From Technology. High Frequency Sealing of Polyolefins in Packaging*, Supplier technology guide, ExxonMobil Chemical, 2003.

30.9 Polyethylene-Acrylic Acid Copolymer

30.9.1 Adhesive Bonding

BASF AG: Lucalen A

Owing to the polarity of the comonomers, the ethylene copolymers, viz. Lupolen V and Lucalen, can be bonded more readily by adhesives than the homopolymers. The adhesion, and thus the strength of the bonds, can be further improved, to an extent depending on the proportion of comonomer, by subjecting the articles to a corona discharge or a similar treatment.

Film that has thus been treated can be very readily joined by means of special adhesives. An example of an application in which this may be required is the production of valve-type block-bottom sacks.

Reference: *Lupolen, Lucalen Product Line, Properties, Processing*, Supplier design guide (B 581 e/(8127) 10.91), BASF Aktiengesellschaft, 1991.

30.10 Cyclic Olefin Copolymer

30.10.1 General

Ticona: Topas

Various welding methods, except for high frequency welding, can be used to join molded parts made from Topas COC resin.

Reference: *Topas Thermoplastic Olefin Polymer of Amorphous Structure (COC)*, Supplier design guide, Ticona, 2000.

30.10.2 Solvent Welding

Ticona: Topas

The solubility of Topas COC resin in various hydrocarbons makes it possible to join parts by solvent welding. Cyclohexane and toluene are suitable solvents for bonding Topas COC resin.

Reference: *Topas Thermoplastic Olefin Polymer of Amorphous Structure (COC)*, Supplier design guide, Ticona, 2000.

31 Polyimide

31.1 Adhesive Bonding

DuPont: Kapton (note: cast with solvent evaporation to form a thermoplastic); **Vespel** (note: precipitated to form a “pseudo thermoplastic” which thermally degrades before its Tg, but is not cross-linked)

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm), and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 31.1 give a good indication of the typical bond strengths that can be achieved as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by

Table 31.1. Shear Strengths of Vespel and Kapton Polyimide to Polyimide Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[d]

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Vespel SP-1	unfilled	1550 (10.7)	2200 (15.2)	350 (2.4)	1650 (11.4)	1150 (7.9)	800 (5.5)
Vespel SP-21	15% graphite	1400 (9.7)	2250 (15.5)	850 (5.9)	2350 (16.2)	550 (3.8)	1000 (6.9)
Vespel SP-22	40% graphite	550 (3.8)	850 (5.9)	400 (2.8)	1000 (6.9)	500 (3.5)	250 (1.7)
Vespel SP-211	15% graphite 10% PTFE	400 (2.8)	550 (3.8)	600 (4.1)	700 (4.8)	200 (1.4)	200 (1.4)
Kapton HN	5 mil thick 500 gauge film	>800[a,b,c] (>5.5)[a,b,c]	>800[a,c] (>5.5)[a,c]	>650[c] (>4.5)[c]	>800[a,c] (>5.5)[a,c]	>800[a,c] (>5.5)[a,c]	>800[a,c] (>5.5)[a,c]
Kapton HPP-ST	5 mil thick 500 gauge film	>800[a,b,c] (>5.5)[a,b,c]	>800[a,c] (>5.5)[a,c]	>600[c] (>4.1)[c]	>800[a,c] (>5.5)[a,c]	>800[a,c] (>5.5)[a,c]	>800[a,c] (>5.5)[a,c]
Kapton HPP-FST	5 mil thick 500 gauge film	>800[a,b,c] (>5.5)[a,b,c]	>800[a,c] (>5.5)[a,c]	>450[c] (>3.1)[c]	>800[a,c] (>5.5)[a,c]	>800[a,c] (>5.5)[a,c]	>800[a,c] (>5.5)[a,c]

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] TAK PAK 7452 Accelerator was used in conjunction with Black Max 380.

[c] The Kapton films were bonded to aluminum lap shears prior to evaluation.

[d] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses)

many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 31.1, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 and Super Bonder 414, both cyanoacrylate adhesives, achieved the highest bond strengths on the Vespel polyimide. Black Max 380, a rubber toughened cyanoacrylate adhesive, achieved the second highest bond strengths. Depend 330, a two-part no-mix acrylic adhesive, and Loctite 3105, a light curing acrylic adhesive, achieved the lowest bond strengths on Vespel. Black Max 380, Prism 401, Super Bonder 414, Depend 330, Loctite 3105, Flashcure 4305, Hysol E-90FL, E-30FL, E-20HP and E-214HP epoxy adhesives, Fixmaster high performance epoxy, and Hysol 3631 hot melt adhesive all achieved substrate failure on the 5 mil (0.005 inch; 0.127 mm) thick Kapton films.

Surface Treatments: The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, resulted in either no effect, or a statistically significant decrease in the bondability of polyimide.

Other Information: When bonding polyimide films, an accelerator may be necessary to speed the cure of cyanoacrylates. Polyimide is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

32 Polymethylpentene

32.1 Adhesive Bonding

Mitsui: TPX RT18

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches/second (0.25 mm/s).

While the bond strengths in Table 32.1 give a good indication of the typical bond strengths that can be achieved as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 32.1, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in

Table 32.1. Shear Strengths of Mitsui Plastics TPX RT-18 PMP to PMP Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[a]

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	3 rms	<50 (<0.3)	150 (1.0)	>1900[b] (>13.1)[b]	250 (1.7)	100 (0.7)	200 (1.4)
Roughened	46 rms	100 (0.7)	500 (3.5)	1000 (6.9)	350 (2.4)	100 (0.7)	200 (1.4)
Antioxidant	0.08% Irganox 1010	<50 (<0.3)	50 (0.3)	>1900[b] (>13.1)[b]	100 (0.7)	<50 (<0.3)	200 (1.4)
UV stabilizer	0.1% Chimasorb 944	50 (0.3)	100 (0.7)	>1900[b] (>13.1)[b]	100 (0.7)	<50 (<0.3)	50 (0.3)
Filler	23% Mica	50 (0.3)	150 (1.0)	>1900[b] (>13.1)[b]	250 (1.7)	150 (1.0)	200 (1.4)
Antistatic	0.3% Armostat 475	<50 (<0.3)	150 (1.0)	>2100[b] (>14.5)[b]	250 (1.7)	<50 (<0.3)	200 (1.4)

[a] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

[b] Due to the severe deformation of the block shear specimens, testing was stopped before the actual bond strength achieved by the adhesive could be determined (the adhesive bond never failed).

"real-world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401, used in conjunction with Prism Primer 770, achieved the highest bond strengths on PMP, typically substrate failure. Loctite 3030 adhesive also obtained outstanding bond strength on PMP. Because of the low surface energy of PMP, all other adhesives performed poorly.

Surface Treatments: The use of Prism Primer 770, in conjunction with Prism 401 or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused a dramatic, statistically significant increase in the bondability of PMP. Surface roughening also resulted in a statistically significant increase in the bond strengths achieved on PMP using cyanoacrylate adhesives, but had no statistically significant effect on acrylic adhesives.

Other Information: PMP can be stress cracked by uncured cyanoacrylate adhesives, so any excess adhesive should be removed from the surface immediately. It is compatible with acrylic adhesives, but can be attacked by their activators before the adhesive has cured. Any excess activator should be removed from the surface immediately. It is incompatible with anaerobic adhesives. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

33 Modified Polyphenylene Oxide

33.1 General

GE Plastics: Noryl

Noryl resins lend themselves to a wide variety of bonding, assembly and fastening techniques as shown in Table 33.1.

Reference: *Noryl Engineering Plastics*, Supplier technical report (CDX-80), General Electric Company.

33.2 Heated Tool Welding

Modified PPO

Under the right conditions, very high strengths (97% of parent) and ductilities (2.4% strain at failure) can be achieved in M-PPO welds made by the heated tool welding process.

Reference: Stokes VK: Toward a weld-strength database for hot-tool welding of thermoplastics. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

Modified PPE

The heat soak time was found to be the critical factor in providing heated tool weld strengths approaching that of the parent material. As contact is made with the stops in 4–8 seconds, the remaining heating time allows increased material softening without further displacement. At 268°C (514°F), to acquire sufficient heat soaked material, it was necessary to have 30–40 seconds heating time. Increasing the hot plate temperature would allow a reduction in the heating time. However, an alternative to a PTFE sleeve would be required to prevent the components sticking to the hot plate.

Although the other heating parameters affected the displacement, the influence on tensile strength was minimal. However, in the weld consolidation period, the effect of pressure on strength was substantial. At higher pressures, strength decreased by more than 10 N/mm^2 (1450 psi). This was presumably because a greater proportion of the material was squeezed from the joint, thereby reducing the amount of material available at the required temperature. For optimum properties, a low pressure and short time, 0.35 N/mm^2 (51 psi) and 5 seconds, would be advantageous in the consolidation stage.

Reference: Watson M, Murch M: Recent developments in hot plate welding of thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

Table 33.1. Joining Techniques Suitable for Use with Noryl Polystyrene Modified Polyphenylene Oxide (PPO)

Bonding	Adhesive Solvent
Welding	Heat sealing Spin welding Resistance wire welding
Mechanical assembly	Heat staking Self-tapping screws Threaded inserts Press fits Induction heat insertion
Ultrasonics	Staking Insertion Bonding

GE Plastics: Noryl

Noryl parts may be bonded together through the use of hot plate or fusion welding. This technique involves taking two mating parts, placing the area to be bonded of each part onto a hot plate, removing the hot plate surface, then forcing the two parts together until the bond has formed.

Reference: *Noryl Design Guide*, Supplier Design Guide (CDX-83D (11/86) RTB), General Electric Company, 1986.

33.3 Ultrasonic Welding

GE Plastics: Noryl

The assembly of two or more parts through the use of ultrasonics may be employed with Noryl resins. Proper design of the mating surfaces and the incorporation of an energy director or shear joint is necessary.

Tensile shear strengths of up to 3000 psi (21 MPa) may be attained in the bond area through the use of this assembly technique. In most cases, the energy director and horn must be oriented in the same direction. Near field design with a high energy input is also recommended.

Each application dictates specific conditions and designs that must be followed. The following may be used as general guidelines:

- Equipment power: 250–3000 W
- Ultrasonic horn: usually one half wavelength at 20 kHz, may be a stepped horn, exponential, catenoidal, rectangular, circular, or booster
- Support jig: proper support design is extremely important to insure that a proper weld is achieved
- Airline pressure: 30–60 psi (0.2–0.4 MPa)
- Weld time: 0.8–2.0 seconds
- Hold time: 1–3 seconds

Noryl may be ultrasonically welded to certain other thermoplastic materials. The use of a common solvent can aid in achieving better welding results. Bond strength will be dependent upon the materials used and the welding conditions.

Glass reinforced grades are more difficult to ultrasonically weld due to the lower amount of substrate material located at the joint surface and the difficulty in molding a sharp energy director. Hermetic seals are usually unattainable with glass-filled materials.

Reference: *Noryl Design Guide*, Supplier Design Guide (CDX-83D (11/86) RTB), General Electric Company, 1986.

33.4 Vibration Welding

GE Plastics: Noryl N190 (form: 3.2 mm (0.126 inch) thick injection molded plaque)

M-PPO welds fairly well to PC/PBT; welds can attain about 73% of the strength of M-PPO using the following welding conditions: frequency of 120 Hz, amplitude of 3.175 mm (0.125 inches), pressure of 0.90 MPa (130 psi), weld penetration of 0.55 mm (0.022 inches) and a weld time of 2.0 seconds.

M-PPO does not weld to PBT.

Reference: Stokes VK: The vibration welding of poly(butylene terephthalate) and a polycarbonate/poly(butylene terephthalate) blend to each other and to other resins and blends. *Journal of Adhesion Science and Technology*, 15(4), p. 499, 2001.

GE Plastics: Noryl 190

Under the right conditions, very high weld strengths can be achieved in 120 Hz cross-thickness welds of M-PPO. Cross-thickness welds do not necessarily attain the highest strengths at the process conditions under which normal-mode welds have high strengths. Therefore, optimum weld conditions for low frequency (120 Hz) welds must be based on cross-thickness weld data.

At a welding frequency of 120 Hz, the cross-thickness weld strength is higher at the lower weld pressure of 0.52 MPa (75 psi), just as in normal-mode welding of this material, and is higher for the lower amplitude of 0.95 mm (0.0375 inches).

At the higher frequency of 250 Hz, excellent cross-thickness weld strength can be achieved in M-PPO and the optimum conditions are the same as for normal-mode welds.

Reference: Stokes VK: Cross-thickness vibration welding of polycarbonate, polyetherimide, poly(butylene terephthalate) and modified polyphenylene oxide. *Polymer Engineering and Science*, 37(4), p. 715, April 1997.

GE Plastics: Modified PPE

The achievable strengths of vibration welds of M-PPO to itself and other thermoplastics are given in Table 33.2.

Reference: Stokes VK: Toward a weld-strength data base for vibration welding of thermoplastics. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

33.5 Spin Welding

GE Plastics: Noryl

The spin welding process requires a specific spin time and a certain non-spin pressure hold time. The variables depend upon which grade of Noryl resin is used and the joint design. Typical conditions are a peripheral speed of 40–50 feet per second (12–15 m/s) and a pressure of 300–400 psi (2.1–2.8 MPa).

Reference: *Noryl Design Guide*, Supplier design guide (CDX-83D (11/86) RTB), General Electric Company, 1986.

33.6 Induction Welding

GE Plastics: Noryl

Noryl parts may be joined by a technique known as electromagnetic induction. Heat is generated directly at the interface by a magnetic field which reaches through the materials being joined. With a properly designed coil, the magnetic field energizes sub-micron size metallic particles uniformly dispersed in the bonding agent producing heat effective for joining.

Reference: *Noryl Design Guide*, Supplier design guide (CDX-83D (11/86) RTB), General Electric Company, 1986.

Table 33.2. Achievable Strengths of Vibration Welds of M-PPO to Itself and Other Thermoplastics

Material Family	M-PPO				
Tensile strength[b], MPa (ksi)	45.5 (6.6)				
Elongation @ break[b], %	2.5				
Specimen thickness, mm (in.)	6.3 (0.25)				
Mating Material					
Material Family[a]	ABS	M-PPO	M-PPO/PA	PC	PEI
Tensile strength[b], MPa (ksi)	44 (6.4)	45.5 (6.6)	58 (8.5)	68 (9.9)	119 (17.3)
Elongation @ break[b], %	2.2	2.5	>18	6	6
Specimen thickness, mm (in.)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)
Process Parameters					
Process type	Vibration welding				
Weld frequency	120 Hz				
Welded Joint Properties					
Weld factor (weld strength/ weaker virgin material strength)	0.76	1.0	0.22	0.24	0
Elongation @ break[b], % (nominal)	1.45	2.4	0.35	0.4	

[a] ABS: acrylonitrile-butadiene-styrene copolymer; M-PPO: modified polyphenylene oxide; M-PPO/PA: modified polyphenylene oxide/polyamide alloy; PC: polycarbonate; PEI: polyetherimide.

[b] Strain rate of $10^{-2} s^{-1}$.

33.7 Heat Sealing

GE Plastics: Noryl

For best results in heat sealing, use hot plate temperatures of 500–550°F (260–288°C) and 20–30 seconds contact time.

Reference: *Noryl Extrusion Resins*, Supplier design guide (CDX-265), General Electric Company.

33.8 Solvent Welding

GE Plastics: Prevex

Solvents that are effective for bonding modified polyphenylene ether (PPE) are: ethylene dichloride, methylene chloride, tetrahydrofuran, toluene, and trichloroethylene.

Solvent that do not dissolve modified polyphenylene ether (PPE) are: acetone, cyclohexanone, dimethyl formamide, ethyl acetate, methyl ethyl ketone, methyl methacrylate, and xylene.

Reference: *Techniques: Adhesive Bonding, Solvent Bonding, and Joint Design*, Supplier technical report (#SR-401A), Borg-Warner Chemicals, Inc., 1986.

GE Plastics: Noryl

Solvent bonding (or welding) is characterized by the use of a chemical agent which dissolves the outer skin of the Noryl resin sufficiently to allow it to be joined together with another Noryl part. The end result of the process after the solvent has evaporated is a true Noryl to Noryl bond, with no intermediate material.

Parts fabricated with Noryl resins may be bonded together through the use of several commercially available solvents, solvent blends and solvent solutions containing varying percentages of Noryl resin. Other thermoplastic resins may be bonded to Noryl with the proper solvent (Table 33.3).

Reference: *Noryl Design Guide*, Supplier design guide (CDX-83D (11/86) RTB), General Electric Company, 1986.

33.9 Adhesive Bonding

GE Plastics: Noryl 731

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a

Table 33.3. Solvent Combinations to Control Evaporation Rate for Noryl Modified PPO Resin

Noryl to Noryl	When the total surface area is less than 1 square foot, and/or the open time is less than 60 seconds.	TCE/MeCl$_2$ 1:1 or TCE/DCE 1:1 by volume for faster evaporation (approx. 15 s)
		TCE for medium evaporation (30 s)
		TCE/MCB 4:1 for slow evaporation (approx. 45 s)
	When more open time is needed or a large area is used:	Use TCE/MCB 1:1 (toluene may be substituted for MCB)
		Use TCE/MCB 4:1, and about 5–25% Noryl weight/vol. If more open time is required, increase MCB by about 10 parts at a time up to a maximum of 60 parts.
Noryl to ABS/PVC	TCE/MCB/THF	1:1:2 by volume
Noryl to ABS	TCE/MEK	4:1 by volume
	TCE/XYL	1:1 volume
Noryl to PVC	XYL/MEK	1:1 by volume mixtures
Noryl to CPVC	THF or THF/TCE	by volume mixtures

DCE: 1,2-Dichloroethylene; CH_2Cl_2: Methylene Chloride, Dichloromethane; MEK: Methyl Ethyl Ketone, 2-Butanone; MCB: Monochlorobenzene, Chlorobenzene; TCE: Trichloroethylene, 1,1,2-Trichloroethylene; XYL: Xylene, Xylol, o, m, p-Xylenes, Dimethyl Benzene; TOL: Toluene, Toluol; THF: Tetrahydrofuran.

thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 33.4 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 33.4, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 and Super Bonder 414 instant adhesives, Flashcure 4305 light cure adhesive, Loctite 3030 adhesive and Hysol E-214HP epoxy adhesive achieved the highest bond strengths on PPO. Loctite 3105, a light curing acrylic adhesive, Hysol E-30CL and E-20HP epoxy adhesives, Hysol U-05FL urethane adhesive, Hysol 3631 hot melt adhesive, Fixmaster high performance epoxy and Fixmaster rapid rubber repair also exhibited good adhesion to PPO. The addition of an antistatic agent or internal lubricant to PPO was found to cause a statistically significant decrease in the bond strengths achieved by the cyanoacrylate adhesives. However, the addition of antistatic agent was determined to cause a statistically significant increase in the bond strengths achieved by Black Max 380 instant adhesive.

Table 33.4. Shear Strengths of Noryl 731-701 Black PPO to PPO Adhesive Bonds Made Using Adhesives Available from Loctite Corporation*

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	7 rms	500 (3.5)	2500 (17.2)	1750 (12.1)	1600 (11.0)	300 (2.1)	950 (6.6)
Roughened	25 rms	500 (3.5)	2500 (17.2)	1750 (12.1)	1600 (11.0)	600 (4.1)	950 (6.6)
Lubricant	9% Polymist F5A	500 (3.5)	1150 (7.9)	1000 (6.9)	1000 (6.9)	300 (2.1)	950 (6.6)
Filler	9% 489 Fiberglass	500 (3.5)	2500 (17.2)	1750 (12.1)	1600 (11.0)	950 (6.6)	500 (3.5)
Antistatic	5% Larostat HTS-904	650 (4.5)	850 (5.9)	600 (4.1)	650 (4.5)	300 (2.1)	950 (6.6)

*All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

Surface Treatments: Prism Primer 770, when used in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused a statistically significant decrease in the bond strengths achieved on PPO. Surface roughening caused a statistically significant increase in the bond strengths achieved by Depend 330, but had no statistically significant effect on any of the other adhesives evaluated.

Other Information: PPO can be stress cracked by uncured cyanoacrylate adhesives, so any excess adhesive should be removed from the surface immediately. PPO is compatible with acrylic adhesives but can be attacked by their activators before the adhesive has cured. Any excess activator should be removed from the surface immediately. PPO is incompatible with anaerobic adhesives. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

GE Plastics: Prevex

The compatibility of generic adhesive groups with modified polyphenylene ether is given in Table 33.5

Reference: *Techniques: Adhesive Bonding, Solvent Bonding, and Joint Design*, Supplier technical report (#SR-401A), Borg-Warner Chemicals, Inc., 1986.

Table 33.5. Compatibility of Generic Adhesive Groups with Modified Polyphenylene Ether (PPE)

Characteristic Evaluated	Material Evaluated	Compatibility Ratings for Generic Adhesive Groups[a]				
		Acrylics	Urethanes	Cyanoacrylates[b]	Epoxies	Silicones
Strength	Prevex PPE	2	5	3	1	5
Impact resistance	Prevex PPE	3	2	5	4	5
Gap filling	Prevex PPE	2	1	5	3	1
Cure time	Prevex PPE	2	5	1	3	3
Ease of application	Prevex PPE	3	4	1	3	2

[a] Compatibility rating guide: 1 - excellent, 2 - very good, 3 - good, 4 - fair, 5 - poor. These ratings are generalizations and will differ for specific brands. Chemical compatibiliity should be evaluated prior to adhesive selection to prevent stress cracking.

[b] Stress cracking is a concern with cyanoacrylates. Careful evaluation of chemical compatibility with the substrate is recommended.

GE Plastics: Noryl

Parts molded of Noryl resins may be bonded to one another as well as to dissimilar materials using a wide range of commercially available adhesives (Table 33.6). Because adhesive bonding involves the application of a chemically different substance between two molded parts, the end-use environment of the assembled unit is of major importance in selecting an adhesive. Operating temperature, environments, bond appearance, unit shape, physical properties, production facilities, equipment costs, and production volumes must all be carefully considered. Epoxy or acrylic adhesives are generally recommended due to their versatile product lines and cure rate schedules.

The following factors should be considered when selecting an adhesive:

- The cure temperature of the adhesive must not exceed the heat deflection temperature of the Noryl resin.
- Adhesives not tested for compatibility with Noryl resins should be avoided or tested.
- Adhesive testing for compatibility should consider operational conditions of temperature and stress.
- Bond strength tests should be conducted on appropriate specimens (i.e. T-peel, impact, tensile shear).

Be sure part surfaces are free of dirt, grease, dust, oil or mold release agents. The surface of the part should be sanded or chromic acid etched before bonding for maximum strength. To insure against misalignment during the cure cycle, apply only “finger-tight” pressure.

Reference: *Noryl Design Guide*, Supplier design guide (CDX-83D (11/86) RTB), General Electric Company, 1986.

GE Plastics: Noryl

There are a multitude of adhesives, and each is usually designed for a broad range of substrates. Below is a brief description of the most common types of adhesives systems recommended for use with Noryl resins.

Single Component: These include various epoxies, cyanoacrylates, urethanes, silicones, nitriles and sulfides. They vary in tensile strength, tack, cure and environmental resistance. Some single component adhesives require a primer.

Two Component: The majority of these are epoxies and urethanes. In some types, the accelerator or catalyst may be mixed into the base. In others, the accelerator may be brushed or sprayed onto one surface while the adhesive is applied to the other. This allows greater open time and ease of assembly.

Hot Melt Systems: These are 100% solids, usually a polymer or polymer blend that is applied as a hot viscous liquid which hardens in minutes to full strength. Polyamides, SBRs, SBNs and EVAs are suitable for a variety of applications. They are fast, easy to use and solventless, so they can meet OSHA standards where solvent systems may be a problem.

Transfer Tapes (pressure sensitive): These are usually 100% adhesive on kraft paper backing, or double-sided adhesive on polyurethane or polyethylene foam tape. Usually the tape is applied to one surface and the backing peeled off so the other substrate can be applied. The 0.020–0.125 inch (0.5–3.2 mm) foam tapes are used generally on irregular surfaces. Tapes offer good shear resistance but generally have poor peel strength. Transfer tapes are widely used in the automotive and appliance industries and when laminating materials.

Reference: *Noryl Extrusion Resins*, Supplier design guide (CDX-265), General Electric Company.

33.10 Mechanical Fastening

GE Plastics: Noryl 731 (features: general purpose grade, 119 Rockwell R hardness); **Noryl GFN2** (features: general purpose grade, 106 Rockwell L hardness; material composition: 20% glass fiber reinforcement); **Noryl GFN3** (features: general purpose grade, 108 Rockwell L hardness; material composition: 30% glass fiber reinforcement); **Noryl HS1000** (material composition: 10% mineral filler; process type: injection molding); **Noryl HS2000** (features: 121 Rockwell R hardness; material composition: 10% mineral filler); **Noryl N190** (features: high impact, flame retardant; process type: injection molding); **Noryl N225** (features: high heat grade, flame retardant, unfilled; process type: injection molding); **Noryl N300** (features: flame retardant); **Noryl SE1** (features: general purpose grade, flame retardant, electronics grade, 119 Rockwell R hardness); **Noryl SE1-GFN2** (features: flame retardant, 106 Rockwell L hardness; material composition: 20% glass-fiber reinforcement); **Noryl SE1-GFN3** (features: flame retardant, 108 Rockwell L hardness; material composition: 30% glass fiber reinforcement); **Noryl SE100** (features: general purpose grade, flame retardant, 115 Rockwell R hardness)

Table 33.6. Recommended Adhesives and Solvents for Noryl Modified PPO Resins

Adhesive	Type	Cure Time/Temperature	Available from
Permabond 910	Methyl Cyanoacrylate	30 s/RT	Permabond Engineering Adhesives
Permabond 101	Ethyl Cyanoacrylate	30 s/RT	Permabond Engineering Adhesives
Permabond 105	Ethyl Cyanoacrylate	30 s/RT	Permabond Engineering Adhesives
Permabond 102	Ethyl Cyanoacrylate	30 s/RT	Permabond Engineering Adhesives
Permabond 240	Ethyl Cyanoacrylate	30 s/RT	Permabond Engineering Adhesives
Super Bonder 420	Ethyl Cyanoacrylate	30 s/RT	Henkel
Super Bonder 495	Ethyl Cyanoacrylate	30 s/RT	Henkel
FFA-5	Epoxy	1 hr/71°C (160°F)	Bacon Industries
Scotch-Weld 2214 (Regular)	Aluminum filled epoxy (1 Part)	40 min/121°C (250°F)	3M
Scotch-Weld 2214 (Hi Temp.)	Aluminum filled epoxy (1 part)	40 min/121°C (250°F)	3M
Scotch-Weld 2214 (Hi Flex.)	Epoxy (1 part)	40 min/121°C (250°F)	3M
Scotch-Weld 1838	Epoxy (2 part)	24 hr/RT	3M
Scotch-Weld 2216	Epoxy (2 part)	24 hr/RT	3M
RTV 103	Silicone	RT	Momentive Performance Materials
RTV 108	Silicone	RT	Momentive Performance Materials
RTV 102	Silicone	RT	Momentive Performance Materials
RTV 116	Silicone	RT	Momentive Performance Materials
RTV 157	Silicone	RT	Momentive Performance Materials
506	Acrylic	4–24 hrs/RT	Lord Corp.
Depend	Acrylic	4–24 hrs/RT	Henkel
Ethylene dichloride	Solvent	1–24 hrs/RT	Chemical supply houses
Chloroform	Solvent	1–24 hrs/RT	Chemical supply houses
Methylene chloride	Solvent	1–24 hrs/RT	Chemical supply houses
Trichloroethylene	Solvent	1–24 hrs/RT	Chemical supply houses
85% Methylene chloride/15% trichloroethylene	Solvent	1–24 hrs/RT	Chemical supply houses

A growing number of products are using housings with lids or covers molded from Noryl resins, especially in the area of small appliances. These lids and housing can be easily designed to incorporate hinge mechanisms, as shown in Fig. 33.1. Noryl resins should not be considered for living hinges.

Riveting: Care should be taken when riveting Noryl resin parts to avoid the high stresses inherent in most

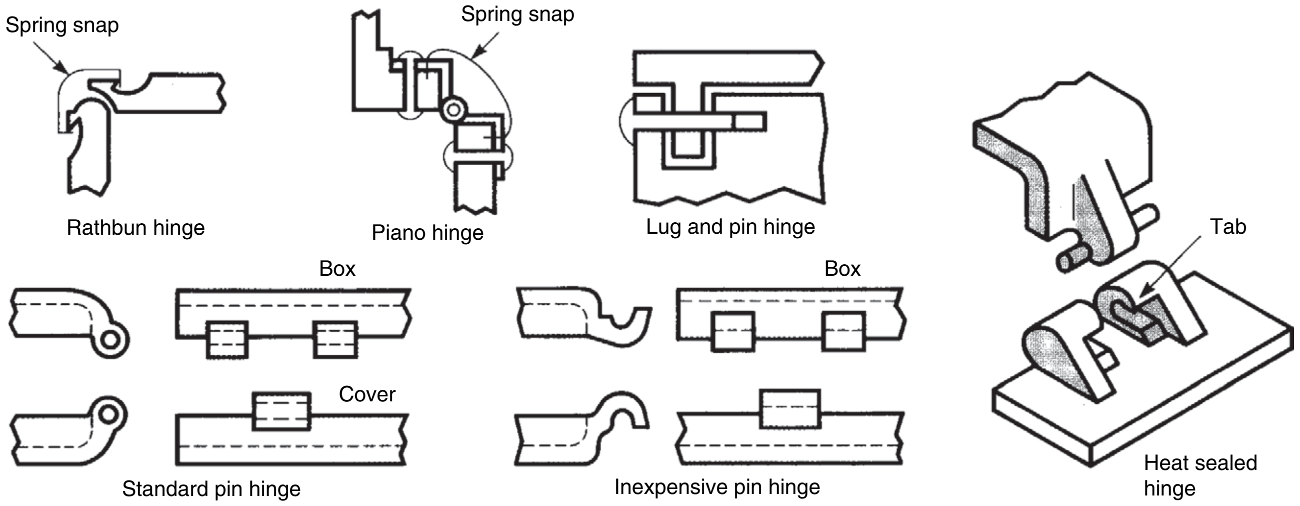


Figure 33.1. Recommended hinge designs for use with Noryl modified PPO resins.

riveting techniques. Using a shouldered rivet limits the amount of stress imposed on the part. Aluminum rivets also limit the force that can be applied, since the aluminum will deform under high stress.

In general, the rivet head should be 2 ½ to 3 times the shank diameter, and the flared end of the rivet should have a washer to avoid high, localized stresses. Clearance around the shaft should allow easy insertion but should not be so great as to allow slippage of the joined parts.

Snap-fit Assemblies: A method of assembly that works well with Noryl resins is the molded snap-fit. Since no additional components are needed, the mating parts can be assembled rapidly and economically on the assembly line, or at the final use location. The following guidelines should be observed in designing the flexing finger:

- Do not exceed the recommended dynamic strain limit (Table 33.7).
- After being snapped into place, the flexing finger should be under little or no stress.
- The snap-fit location should be planned so there are no sharp corners, gates, or knitlines on the flexing finger, which could lead to shortened life.
- A snap-fit assembly is generally used less than 10 times. If a large number of cycles is expected, fatigue life could be a consideration and a lower strain limit may be required.
- Designers should remember to consider stress concentration factors.

A tapered beam will provide a more efficient equally stressed flexing finger. Several methods for forming snap-fingers are available. A snap-finger design that does not require a side core in the mold is preferred.

Staking: Heat staking is an assembly technique possible with Noryl resins. Depending upon the grade, temperatures will range from 450 to 550°F (230–290°C). It is similar to ultrasonic staking but the forming head is heated and temperature controlled. The equipment can be shop made or purchased and is relatively inexpensive.

Unlike ultrasonic welding of Noryl resins, staking requires that out-of-phase vibrations be generated between the horn and plastic surfaces. Light, initial contact pressure is therefore a requirement for out-of-phase vibratory activity within the limited contact area. It is the progressive melting of plastic under continuous, but light pressure that forms the head. Adjustment of the flow-control valve and trigger switch may be required to reduce pressure to the desired level.

Optimum staking conditions depend upon part design and the particular Noryl resin used, but typical staking conditions for a 1/8 inch (3.2 mm) diameter stud of unfilled resin are:

- Pressure: 12 psi (0.083 MPa)
- Weld Time: 0.25–0.6 seconds
- Hold Time: 1 second

Threaded Fasteners: Metal screws and bolts are commonly used to assemble Noryl resin parts or for attaching various components. Common bolted assemblies are:

- Through nut and bolt - in this case, the metal assembly puts the Noryl resin part into compression

Table 33.7. Maximum Recommended Dynamic Strain Limits for Snap-fit Assemblies Using Noryl Modified PPO Resins

Resin Used in Snap Finger	% Strain in Snap Finger	Calculated Value of Dynamic Strain
N190, N225, N300	8	0.08
731, SE1, SE100	8	0.08
HS1000, HS2000	8	0.08
SE1-GFN2, GFN2 SE1-GFN3, GFN3	3	0.03

under the bolt and nut. The following guidelines must be observed:

  - The Noryl resin parts must go into compression without causing high bending stresses or distortion at the molded part. The loose-fit "gap" should only be large enough to make the assembly a snug-fit.
  - Uncontrolled assembly torques with this type of assembly can cause excessive compression forces in the molded parts. The resultant compressive stress due to the assembly torque is the axial force divided by the area under compression. If the resultant compressive stress is beyond the recommended working stresses, either the torque must be controlled to a lower value, or the areas under compression must be increased with a larger screw head or with metal washers.
  - Since the areas are usually under moderate stress, lubricants, oils, thread locking compounds, and other substances should be avoided.

- Attaching to metal part—this is similar to the through bolt and nut design, and excessive compression stress can create problems. If large washers or lower torque are not practical, a shoulder screw or stepped washer is a practical solution.

Tapping and Self-tapping Screws: When using Noryl thermoplastic resins in injection molded parts, the use of thread-cutting self-tapping screws, such as ASA Type "T" (Type 23) or ASA Type "BT" (Type 25) is recommended. This type of screw cuts its own threads during installation, and has a slot cut out of the bottom to provide a channel in which the chips may accumulate. Thread-cutting screws offer the advantage of low residual stresses in the area around the boss.

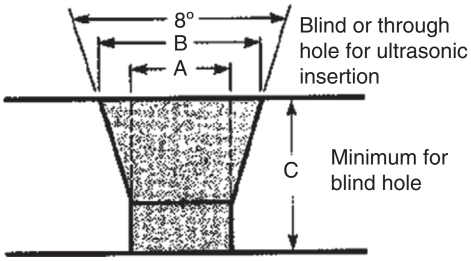
General design criteria for using self-tapping screws with Noryl resins are:

- The receiving hole diameter should be equal to the pitch diameter of the screw.
- Boss OD should be adequate to resist possible hoop stresses developed during insertion. Usually, a boss OD equal to twice the screw diameter is sufficient.
- Thread engagement should be at least twice the screw major diameter. A small increase in thread engagement will result in a significant increase in pull-out strength, however, an increase in screw diameter will result in only a minimal increase in pull-out strength.
- Boss height should not exceed two times the boss OD. Hole depth should be slightly longer than the screw length, to allow for chip accumulation.
- Repeated assembly operations are not recommended.
- Use minimum torque to keep screw assembly stress within the design limits of the material.

Residual stresses created by screws other than thread-cutting screws are near or exceed the suggested design limits. Boss caps are recommended if self-tapping screws are used for repeated assembly. The advantages of this type of assembly include a 50% increase in pull-out retention, doubled torque retention, minimized hoop stress and greater protection of the boss compared to thread-forming, self-tapping screws.

Bosses: A boss cap is a cup-shaped metal ring which is pressed onto the boss by hand, with an air cylinder, or with a light-duty press. It is designed to reinforce the boss against the expansion force exerted by self-tapping screws, and works well with Noryl resin parts in light duty applications.

Ultrasonic Inserts: Ultrasonic insertion is a fast and economical method of installing metal inserts into parts molded of Noryl resin. This technique offers a high degree of mechanical reliability with excellent pull-out and torque retention combined with savings resulting from rapid production cycles. If the assembly is properly designed, ultrasonic insertion results in lower residual stress compared to molded-in or pressed-in techniques since a uniform melt occurs and a minimum amount of thermal shrinkage is involved. Figure 33.2 offers recommended hole designs for inserts used with Noryl resins. Molded-in inserts are not recommended with most Noryl resins due to the coefficient of thermal expansion (CTE) differential between the unreinforced resin grades and the metal insert.



Thread size	Insert O.D. (Inches)	Insert length (Inches)	Dia. A (Inches)	Dia. B (Inches)	Depth C (Inches)
4–40	0.171	0.250	0.136	0.164	5/16
6–32	0.217	0.312	0.177	0.210	3/8
8–32	0.250	0.375	0.199	0.240	7/16
10–24	0.296	0.438	0.234	0.280	1/2

Figure 33.2. Recommended hole designs for ultrasonic inserts in Noryl modified PPO resins.

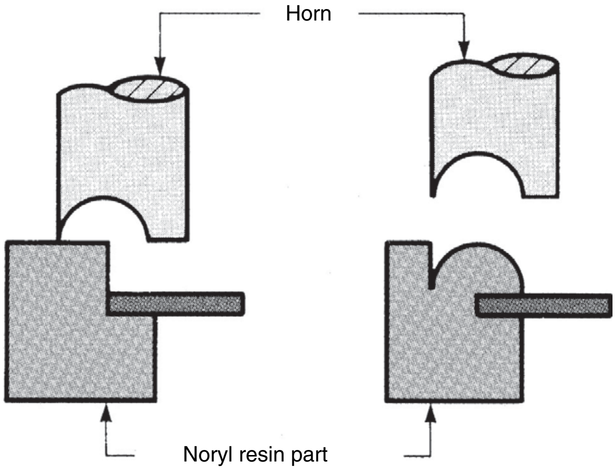


Figure 33.3. Ultrasonic Swaging.

Ultrasonic Swaging: Ultrasonic swaging (Fig. 33.3) is a process of melting and reforming a ridge of Noryl resin to mechanically encapsulate another component of an assembly. This method may be used with Noryl under the following general considerations:

- Low amplitude
- Medium to high pressure
- Rigid fixturing
- Slow to medium carriage speed

Reference: *Noryl Design Guide*, Supplier design guide (CDX-83D (11/86) RTB), General Electric Company, 1986.

34 Polyphenylene Sulfide

34.1 Heated Tool Welding

Ticona: Fortron

This method is preferably employed for joints exposed to mechanical stress in service, large joint surfaces or part geometries that preclude the use of other welding methods. It is important to ensure that the heated tools used are designed for the high temperatures required.

Reference: *Fortron Polyphenylene Sulphide*, Supplier design guide, Ticona, 2000.

34.2 Ultrasonic Welding

Chevron Phillips Chemical: Ryton

Ryton PPS compounds are relatively easy to weld together. Joint design is, however, critical to the finished part strength. A shear joint is the best overall, although the step joint has been used successfully with Ryton PPS R-4. The shear joint will generally be six times stronger than the step joint.

When welding shear joints, use high power with a high amplitude booster, low pressure, and slow horn speed. When welding the parts, caution should be used since too high an amplitude and/or too long an application time could destroy the part.

Shear joints are usually not recommended for parts with a maximum dimension of 3.5 inches (89 mm) or greater, sharp 90° turns, or irregular shapes, due to the difficulty of holding the required molding tolerances. Ryton PPS may extend these limits, however, since it can hold tight molding tolerances.

Reference: *Ryton Design Guide,* Supplier design guide, Chevron Phillips Chemical Company LP, 2004.

Ticona: Fortron

Fortron moldings can be joined by the usual ultrasonic assembly methods. Joints produced have high strength. Fortron is suitable for both near- and far-field ultrasonic welding. However, because of the relatively brittle-hard behavior of the material, it should be borne in mind that the alternating strains that have to be absorbed by the parts being joined can lead to localized damage. Additions of up to 40% reinforcing materials still permit good welding results. With higher additions, however, weldability deteriorates.

Reference: *Fortron Polyphenylene Sulphide,* Supplier design guide, Ticona, 2000.

LNP Engineering Plastics: OF1006 (material composiition: 30% glass fiber)

Polyphenylene sulfide, being a semi-crystalline thermoplastic, is not ideally suited to ultrasonic welding. In a semi-crystalline plastic the amorphous portions soften at a low temperature with a corresponding increase in mechanical loss factor, which results in more energy being needed to melt the crystalline portions. This phenomenon is reflected in the results of the weldability trials.

The results of the weldability study suggest that joints can be formed so long as sufficient power is applied to the joint, that is, it is necessary to employ a high vibration amplitude and to contact the welding horn as close as possible to the joint. A projection joint has proved to be the most successful joint design. Far field welding is not feasible for this material.

The ultrasonic welding of 30% short glass fiber filled PPS was studied using a 1500 W commercial ultrasonic welding machine. Projection and shear joints were used for weldability trials. The effect of the base fixturing material was investigated by comparing aluminum, Devcon and PTFE.

- 30% short glass fiber PPS (grade LNP OF-1006) can be welded by ultrasonics in the near field. A high vibration amplitude, 80 μm (0.003 inches) and low weld force, 275 N (61.8 lbf), is required to ensure that sufficient heat is generated at the joint. Poor tolerance to variations in welding parameters means that critical optimization of welding procedures is required.
- If ultrasonic welding is required, the quality of the injection molded component is of great importance. Defects in the molding, such as internal weld lines, affect ultrasonic energy transmission and can act as energy absorbers within the component. This results in damage to the specimen, either cracking or overheating, and poor joint quality as a result of insufficient energy availability at the weld line.

- The fixturing material affects the weld quality. In the present trials, a PTFE fixture gave a wider tolerance to welding parameters and less scatter than aluminum, but did not improve the maximum joint strength achieved.

Reference: Taylor N: The ultrasonic welding of short glass fibre reinforced thermoplastics. ANTEC 1991, Conference proceedings, Society of Plastics Engineers, Montreal, May 1991.

34.3 Spin Welding

Ticona: Fortron

For Fortron moldings with rotationally symmetrical joint faces, spin welding is a suitable assembly method to obtain gas-tight, high strength joints. The most suitable welding conditions, such as surface speed, contact pressures and rotational speeds, will depend on the Fortron grade and part geometry and must be determined by optimizing trials.

Reference: *Fortron Polyphenylene Sulphide,* Supplier design guide, Ticona, 2000.

34.4 Laser Welding

Ticona: Fortron

In the laser welding process the laser beam has to be transmitted through the first welding part and absorbed by the second one. Trials with Fortron grades showed that reinforced ones have a good absorption behavior. The wall thickness for the first (laser-permeable) part made of unfilled Fortron should be less than 2 mm (0.079 inches).

Reference: *Fortron Polyphenylene Sulphide,* Supplier design guide, Ticona, 2000.

34.5 Infrared Welding

Bayer: Tedur 9611 (reinforcement: 45% glass fiber)

Due to the orientation of the glass fibers, the bulk material specimen (3 mm; 0.118 inch thick plates) showed a strength of 120 MPa (17,400 psi) parallel to the welded line and 80 MPa (11,600 psi) normal to it. In tests showing the actual weld strength of IR welded polyphenylene sulfide (PPS) plates as a function of weld layer thickness, PPS does not show a minimum in strength. At the same time, the range of melt layer thicknesses resulting in optimal strengths is comparable to that in heated tool butt welding. The obtained strengths of PPS welded seams exceeded 45 MPa (6530 psi). This corresponds to a welding factor of approximately 0.6 for a base material strength of 80 MPa (11,600 psi).

Reference: Potente H, Michel P, Heil M: Infrared radiation welding: a method for welding high temperature resistant thermoplastics. ANTEC 1991, Conference proceedings, Society of Plastics Engineers, Montreal, May 1991.

34.6 Resistive Implant Welding

PPS (reinforcement: continuous carbon fiber and glass fiber)

An experimental study on resistance welding of glass fiber and carbon fiber PPS based composites with a metal mesh heating element was performed.

The welding pressure showed a relatively limited effect on the weld strength for both materials investigated. The results showed that, for an intermediate power level (110 kW/m^2), a pressure between 0.6 and 1.0 MPa (87–145 psi) is needed. Welding pressures below this range lead to deconsolidation and very high void content, resulting in weak bonding. Welding pressures above the optimal range lead to excessive squeeze flow and dry bonds with low mechanical properties.

It was noted that, due to a much higher heat transfer coefficient of the carbon fibers in the longitudinal direction, carbon fiber reinforced specimens needed substantially more energy than glass fiber ones to reach the optimal weld range. For lower power levels, the difference mounted up to three times the energy input for glass fiber specimens.

Reference: Stavrov D, Bersee HEN, Beukers A: Resistance welding of continuous fibre reinforced PPS composites with metal mesh heating element. Innovation and Integration in Aerospace Sciences, Conference proceedings, Belfast, UK, August 2005.

34.7 Induction Welding

PPS (reinforcement: carbon fiber fabric)

In order to prove the efficiency of the continuous induction welding process for fabric-reinforced thermoplastics, the characteristics of single-lap welded specimens were determined in tensile shear tests and by means of microscopy. The laminates to be joined were moved on a slide in relation to the inductor and were heated up to the processing temperature by an electromagnetic field. After the heating operation, a press-on roller applied the welding force and, at the same time, absorbed the heat from the welded component so that the matrix polymer resolidified.

Results showed that the greatest weld strength was achieved at a welding force of 200–300 N (45–67 lbf). With regard to the advance, there was an almost linear decrease in the weld strength as the advance speed increased. Photomicrographs of the welded joints showed that complete welding occurred at low advance speeds, up to 3.6 mm/s (0.14 inches/s), so that the weld could no longer be distinguished from the rest of the laminate. The number and scope of the delaminations (disbonding of one laminate layer from another) and of the air inclusions in the laminate increased along with the advance speed. The time of action of the welding force was obviously no longer sufficient to eliminate the delaminations arising during the molten phase and to consolidate the laminate once again.

Reference: Rudolf R, Mitschang P, Neitzel M: Induction welding of fabric-reinforced fibre-plastic composites. *Schweissen und Schneiden*, 53(10), p. 690, October 2001.

34.8 Adhesive Bonding

GE Plastics: Supec

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1"× 1"× 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 34.1 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example,

Table 34.1. Shear Strengths of Supec PPS to PPS Adhesive Bonds Made Using Adhesives Available from Loctite Corporation*

Material Composition		**Loctite Adhesive**					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Supec grade W331	30% glass reinforced PTFE filled 9 rms	100 (0.7)	150 (1.0)	400 (2.8)	250 (1.7)	150 (1.0)	550 (3.8)
Grade W331 roughened	24 rms	150 (1.0)	500 (3.5)	400 (2.8)	400 (2.8)	350 (2.4)	550 (3.8)
Grade G301T	30% glass reinforced	200 (1.4)	400 (2.8)	150 (1.0)	350 (2.4)	250 (1.7)	1200 (8.3)
Grade G401	40% glass reinforced	200 (1.4)	300 (2.1)	300 (2.1)	300 (2.1)	450 (3.1)	1100 (7.6)
Grade G323	65% glass/mineral filled	250 (1.7)	400 (2.8)	900 (6.2)	600 (4.1)	300 (2.1)	2050 (14.1)
Grade CTX530	30% glass reinforced PPS/PEI blend	150 (1.0)	250 (1.7)	400 (2.8)	400 (2.8)	200 (1.4)	900 (6.2)

*All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 34.1, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in “real world” applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Flashcure 4305 light cure adhesive and Hysol E-30CL and E-214HP epoxy adhesives achieved the highest bond strengths on the standard grade of PPS evaluated. In general, all the adhesives tested exhibited good adhesion to PPS. The exceptions are Black Max 380 instant adhesive, Loctite 3340 light cure adhesive, hot melt adhesives and Loctite 5900 flange sealant.

Surface Treatments: Surface roughening caused a statistically significant increase in the bond strengths achieved by all the adhesives evaluated, with the exception of Loctite 3105 light cure adhesive and Prism 401 instant adhesive, both of which experienced no statistically significant change. The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, did not produce any statistically significant change in the bondability of PPS.

Other Information: PPS is compatible with all Loctite adhesives, sealants, primers, activators, and accelerators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

Chevron Phillips Chemical: Ryton

There are many adhesives that will bond Ryton PPS compounds, provided the surface is properly prepared to allow the adhesive to wet the surface.

Reference: *Ryton Design Guide*, Supplier design guide, Chevron Phillips Chemical Company LP, 2004.

Ticona: Fortron

The high solvent resistance of Fortron permits only contact adhesion. Depending on the application, two-pack adhesives based on epoxy resin, methacrylate or polyurethane, one-pack adhesives based on cyanoacrylate or hot melt adhesive may be used.

Reference: *Fortron Polyphenylene Sulphide,* Supplier design guide, Ticona, 2000.

34.9 Mechanical Fastening

Chevron Phillips Chemical: Ryton

Snap-fit Assemblies: High strength and rigidity of Ryton PPS compounds provide good holding strength with a minimum of flex and interference. Typically, Ryton PPS snap-fit applications involve only one time assembly.

Rivets: Ryton PPS can be successfully assembled using semi-tubular style rivets. The definition of a semi-tubular rivet is a rivet whose mean hole depth, measured on the wall, does not exceed 112% of its mean body diameter. This design will put less stress on the molded parts, especially if the distance between the hole and the underside of the head is the same as the combined material thickness. In order to ensure that minimum stress is placed on the molded parts during riveting operations, it is essential that the rivet setter be adjusted to exert the minimum impact required to clinch the rivet.

Tapped Threads for Bolts: In most applications where repeated assembly and disassembly is not required, Ryton PPS moldings with tapped threads work very well. Tapped holes in Ryton PPS glass mineral filled compounds have excellent bolt holding power. Bolts screwed into a depth of four bolt diameters equaled or exceeded the tensile strength of brass and mild steel bolts. Bolts screwed in three turns and those at two bolt diameters also had excellent strength.

Self-tapping Screws: The excellent creep resistance of Ryton PPS makes it well suited for assembly with self-tapping screws. Due to the hardness of Ryton PPS compounds, thread-cutting types, rather than thread-forming types, perform best.

Ultrasonic Inserts: Ryton PPS can be conveniently assembled using ultrasonic inserts. Inserts of these types are recommended when repeated disassembly is required, and good pull-out strength is desirable.

Molded-in Threads: Because of the excellent processability of Ryton PPS, molded-in threads can be designed into most parts. This will eliminate the need for expensive secondary machining operations. Molding in the threads should also provide superior performance, as compared to machined threads, due to the normal skin effect on injection molded parts.

Molded-in Inserts: Because of the excellent processability of Ryton PPS, molded-in inserts can be designed into many parts. Molded-in inserts may be used when repeated assembly and disassembly of parts is required. Since Ryton PPS easily molds around inserts, excellent pull-out strengths should be expected. Inserts are recommended when an appreciable amount of preload is desired. The insert should be designed such that the load is carried through the metal insert and not the plastic. Flanged type inserts work well for highly loaded applications.

Heat Staking: The optimum process conditions for a typical 1/8 inch (3.2 mm) diameter post might be, for an amorphous part, a tip temperature of 590°F (310°C). For a crystalline part, use a tip temperature of 620°F (327°C). The downward force is typically 150 lbf (68 kgf) applied for 40 seconds. Since the staked area will be amorphous after the melt/deformation, the assembly should be annealed at 400°F (204°C) for 2 hours if the application requires a fully crystalline part. Since all glass reinforced compounds can be abrasive, we recommend the staking tip be made of a hardened steel with a Rockwell C rating of 60 or greater.

Reference: *Ryton Design Guide,* Supplier design guide, Chevron Phillips Chemical Company LP, 2004.

Ticona: Fortron

Snap-fit Assemblies: Fortron is a rigid-hard engineering plastic for which the low-cost, snap-fit assembly technique can be used. For this method to be successful, it is important to ensure that the snap-fit elements are correctly designed. The following guide values for outer-fiber strain should be regarded as an upper limit:

- Fortron 1131L4, 1140L4, 1140L6: 1.3%
- Fortron 4184L4, 4184L6: 1.1%
- Fortron 6165A4, 6165A6: 0.8%

The friction factor, which is necessary for the calculation, depends on the sliding partners, surface roughness and surface pressure. Typical with Fortron are:

- Fortron/Fortron: 0.3–0.4
- Fortron/steel: 0.4

Assembly with Screws: Due to the low expansibility in comparison with other polymers, Fortron cannot compensate stress peaks in the same way and is very sensitive to notches. For these reasons, part shapes with a very high stress should be designed with more attention. For parts made of Fortron, the following screw methods have been used: molded threads, molded-in inserts, and bolting with through bolts and direct bolts (e.g., self-tapping screws).

Reference: *Fortron Polyphenylene Sulphide,* Supplier design guide, Ticona, 2000.

35 Polypropylene

35.1 Polypropylene General

35.1.1 General

Hoechst AG: Hostacom (reinforcement: glass fiber)

Hot gas welding, heated tool welding, friction welding and vibration welding are all suitable methods for welding Hostacom. Ultrasonic welding is possible only under "near field" conditions.

Hostacom moldings are only conditionally suitable for weld designs in the context of semifinished product processing (chemical apparatus engineering).

Reference: *Hostacom Reinforced Polypropylene*, Supplier design guide (B115BRE9072/046), Hoechst AG, 1992.

Hoechst AG: Hostalen

All Hostalen polypropylene (PP) pressurized pipe materials can be combined homogeneously and permanently with each other, through heating tool socket fusion welding, and also with heated tool butt welding or extrusion welding. A variety of weld fittings is also available, including fittings for connecting plastic to metal such as socket welds with metal thread inserts or clamp screw couplings.

Reference: *Future—The Hoechst Magazin*e, Supplier newsletter (HB920EBR/014), Hoechst, 1992.

Doeflex Industries Limited: PP (process type: thermoforming; form: sheet)

Polypropylene is a nonpolar, chemically inert material and cannot be welded using the high frequency equipment that is commonly used for flexible PVC. However, thermal bonding techniques work well. In some fields, polypropylene moldings and thick sheets are welded by using hot gas, hot plate, or friction techniques. These methods have not been found useful for Doeflex polypropylene binders.

Reference: *Thermoforming with Polypropylene and Polyethylene,* Supplier data sheets, Doeflex Industries Limited.

35.1.2 Heated Tool Welding

PP (form: foam)

Welding factors of 0.9 and above were attained.

Reference: Potente H, Wilke L: Welding thermoplastic foams. ANTEC 2005, Conference proceedings, Society of Plastics Engineers, Boston, May 2005.

PP

The thickness of the HAZ was approximately 420 μm (0.017 inches) for hot plate welds made using the following welding parameters:

- Hot plate temperature: 516 K (244°C; 471°F)
- Matching time: 30 seconds
- Matching pressure: 659.3 kPa (95.6 psi)
- Heating time: 35 seconds
- Change-over time: 1.5 seconds
- Forging time: 60 seconds
- Forging pressure: 741.7 kPa (107.6 psi)

Reference: Krishnan C, Toussant D, Benatar A: Comparison of weld morphology of polycarbonate and polypropylene for hot plate, vibration and ultrasonic welding. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

PP (reinforcement: nanoclay)

Hot plate welding was used to investigate the weldablity of polypropylene nanocomposites containing 0, 3, and 6 wt.% nanoclay. A three-factor (heating temperature, heating time, forging pressure), two-level design of experiments was used to analyze and optimize the welding parameters.

The maximum weld strength measured for 0 wt.% nanoclay samples was 22.6 MPa (3,280 psi), which is 93.7% of the bulk material strength. For 3 wt.% nanoclay samples, the maximum weld strength was 19.9 MPa (2,890 psi) (79.4% of bulk material strength), and for 6 wt.% nanoclay samples, the maximum weld strength was 16.2 MPa (2,350 psi) (62.2% of bulk material strength), indicating that weld strength drops as the amount of nanoclay increases in the samples. These adverse effects include lower ductility of the weld as determined from examination of the fracture surfaces and thinner melt layers, as observed from cross-sectional micrographs.

Reference: Mokhtarzadeh A, Benatar A, Wu CY: Experiments in hot plate welding of polypropylene nanocomposites. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

PP (reinforcement: 20% glass fiber; form: injection molded ISO tensile test specimen)

The depth of the zone that melted during the heating stage of the welding process (L_0) was measured by microscopy on cross-sections taken from heated, but not welded bars. For every weld, the values of L_0 and of the welding displacement (d) allowed the determination of the ratio of melt displacement ($RMD = d/L_0$).

The best welding temperature appeared to be around 260°C (500°F). Welding caused transverse orientation of the fibers at the weld zone. The RMD affects the level of transverse orientation of the fibers and the occurrence of voiding. These features have a detrimental effect on the weld strength.

Reference: Oliveira MJ, Duarte FM, Tchalamov D, Cunha AM: Hot plate welding of glass reinforced polypropylene. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

Ticona: Celstran PP (reinforcement: long glass fiber)

Regardless of fiber content, heated tool welding yields the highest values for weld strength. The weld strength achieved with Celstran PP is between 25 and 40 MPa (3,630–5,800 psi) using the following welding parameters:

- Hot plate temperature: 260°C (500°F)
- Heating time: 10–20 seconds
- Heating pressure: 0.5–0.6 MPa (73–87 psi)
- Welding pressure: 0.5–0.6 MPa (73–87 psi)

or, for high temperature hot plate welding:

- Hot plate temperature: 360°C (680°F)
- Heating time: 5–10 seconds
- Heating pressure: 0.4–0.5 MPa (58–73 psi)
- Welding pressure: 0.4–0.5 MPa (58–73 psi)

Reference: *Celstran, Compel Long-Fibre-Reinforced Thermoplastics (LFT)*, Supplier design guide, Ticona, 2001.

PP (filler: talc)

Polypropylene samples with 0% (pure), 20%, and 40% talc were welded using hot plate temperatures of 250°C (482°F) and 290°C (554°F). Heating times ranged from 10 to 80 seconds and the welding pressure was kept constant at 1.379×10^5 Pa (20 psi).

It was found that the maximum joint strength depended on the talc concentration. The maximum joint strength for 0% and 40% talc reinforced PP was 97% and 54% of the bulk strength, respectively. For talc-reinforced PP, the joint strength was low, and the energy at break was well below 0.5 J. This shows the limitation of intermolecular diffusion at the joint interface that results from the transverse orientation and high concentration of talc filler at the joint interface.

Reference: Wu CY, Poopat B, Benatar A, Park JB: Hot plate welding of polypropylene and talc reinforced polypropylene composites. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

PP (reinforcement: glass fiber; fillers: chalk and talcum)

The research results have shown that there is a material-specific limit on the maximum attainable weld strength for filled and reinforced material systems that cannot be exceeded, despite extensive variation of the process conditions.

The results of the parameter study conducted on glass-fiber reinforced polypropylene have shown that the attainable weld strength $\sigma_{schw(\varphi)}$ is a function of the following parameters:

- Glass fiber content, φ
- Yield stress of the unreinforced reference specimen, $\sigma_{GM(\varphi=0)}$
- Weld strength of the matrix material, $\sigma_{schw(\varphi=0)}$
- Yield stress of the glass fiber reinforced reference specimen, $\sigma_{GM(\varphi)}$

Reference: Potente H, Brüßel A: Welding behaviour of filled and reinforced thermoplastics with hot plate welding. ANTEC 1998, Conference proceedings, Society of Plastics Engineers, Atlanta, May 1998.

PP (reinforcement: glass fiber)

Hot plates were designed with different profiles. Two knurled shapes were selected as surface structures for the hot plate. One of these was a knurl with axially parallel ridges and one was a cross-knurl. An interval of 1 mm (0.039 inches) was selected for the distance between the knurl ridges. A flat hot plate surface was also used by way of comparison. No coating was applied to the hot plate surfaces. Identical heating conditions were chosen for all the welding tests. The temperature of the hot plate was 250°C (482°F) and the heating time was 40 seconds.

The results showed that, when glass-fiber reinforced materials are joined by heated tool welding, even with the use of profiled hot plates, it is still not possible to exceed a maximum welding factor of "1" minus the glass-fiber component.

Reference: Potente H, Brüßel: Investigations into increasing weld strength through the use of profiled hot plates. ANTEC 1997, Conference proceedings , Society of Plastics Engineers, Toronto, May 1997.

PP

Results showed that when either time or temperature is increased, the weld strength increased until a maximum is reached. This was at 75% of the normal sample strength for PP.

Reference: Rapai J: Tensile strength evaluation of hot plate welds in polypropylene and polyethylene. ANTEC 1997, Conference proceedings, Society of Plastics Engineers, Toronto, May 1997.

PP (form: random long fiber glass mat)

In PP-reinforced with random long fiber glass mat, the fibers are ineffective for reinforcing heated-tool butt welds. The maximum weld strengths attained with this glass mat reinforced thermoplastic (GMT) are comparable to the strengths of good welds of the unfilled material. The optimum heated-tool welding parameters for the reinforced materials are different from those for the unfilled material.

Reference: Gehde M, Giese M, Ehrenstein GW: Welding of thermoplastics reinforced with random glass matt. *Polymer Engineering and Science,* 37(4), p. 702, April 1997.

PP

The effect of hot plate welding parameters on the butt weld strength of polypropylene plates was investigated. Increasing the heating time increased the weld strength and the heating displacement. Increasing the heating pressure decreased the weld strength. Increasing the change-over time decreased both the weld strength and welding displacement. Increasing the hold time increased weld strength, and increasing the welding pressure decreased the weld strength.

Reference: Lin TT, Benatar A: Effects of hot plate welding parameters on the weld strength of polypropylene. ANTEC 1993, Conference proceedings, Society of Plastics Engineers, New Orleans, May 1993.

PP

This study focused on the effects of heating temperatures and heating times on the microstructure and properties of the hot plate weld. Polypropylene was used due to its large crystal structure, which could be observed easily under a microscope. The goal was to find the correlation between microstructure and weld quality in hot plate welding.

The characterization of the heat-affected zone (HAZ) around welds plays a prominent role in determining the weld quality. The influence of HAZ microstructure on the weld strength was investigated by comparing micrographs of microtomed samples and their tensile strength. The weld joints which had less in homogeneity along the joining interface had better weld quality. High heating temperatures might be applied to reduce the welding cycle time. However, the heating time should be carefully selected in such cases, since the weld quality was very sensitive to the variation of heating time.

Reference: Nieh JY, Lee LJ: Morphological characterization of the heat-affected zone (HAZ) in hot plate welding. ANTEC 1993, Conference proceedings, Society of Plastics Engineers, New Orleans, May 1993.

PP

In heated tool welding of polypropylene, tensile strengths approaching that of the parent material can be achieved with displacements of about 2 mm (0.079 inches). An important aspect was the heat-soak time, which was influential in obtaining high joint strengths. Ideally, the stops should be as close to the joint interface as possible, consistent with bringing the joint interface into intimate contact with the heating element. After displacement stops were reached, the heating time controlled the amount of heat soak. The optimum range found for heating time was 10–20 seconds. Without the application of displacement limit stops the heat-soaked material was squeezed out during the heating stage, thus giving joints of low strength.

The hot plate temperature was found to be a less critical parameter than either heating pressure or time. Although the material displacement increased substantially with increasing temperature, the joint strength remained around 30 N/mm^2 (4,350 psi) for platen temperatures between 215 and 260°C (419–500°F).

Two process parameters were involved in the weld consolidation stage: consolidation pressure and time. The pressure affected the material displacement, with the major portion occurring within 2 seconds of application. The consolidation time showed no discernible trends on either material displacement or tensile strength beyond 5 seconds.

Reference: Watson M, Murch M: Recent developments in hot plate welding of thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

Solvay: Fortilene

Heated tool welding can assure a virtually 100% air, water, or dust seal, and has found great acceptance in the welding of polypropylene battery cases. Large parts such as refrigerator or washing machine doors, small parts, and parts with irregular shapes, or thick walls can all be welded by fusion welding.

Reference: *Fortilene Polypropylene Properties, Processing, and Design Manual,* Supplier design guide, Soltex, 1981.

35.1.3 Ultrasonic Welding

PP

The ultrasonic spot welding process is an attachment method for PP-based Dual Lock reclosable fasteners to PP substrates, and has many benefits. The ultrasonic bonding method provides very strong, almost permanent bonds that are relatively insensitive to temperature and humidity conditions. The total weld strength is easily adjustable based on the number of spot welds per unit area.

Reference: Kobe JJ: Ultrasonic bonding of 3M™ Dual Lock™ reclosable fasteners to polypropylene substrates. ANTEC 2006, Conference proceedings, Society of Plastics Engineers, Charlotte, May 2006.

PP (form: nonwoven fabric)

Polypropylene blown microfibers with spun-bonded cover web made from PP and polyester fibers were used for the experimental study of the ultrasonic plunge welding of nonwovens. Major uses of spun-bonded nonwoven fabrics are for carpet packing, in bedding and home furnishing, as well as disposable apparel, including diapers and sanitary goods, durable papers, and coated fabrics.

There are three primary ultrasonic variables that will affect the quality of bonding: vibration amplitude, welding time, and welding pressure. Different welding profiles with distinct shapes were added as a fourth variable.

Ultrasonic plunge welding of PP nonwoven fabrics was performed using a central composite DOE. It was found that welding pressure had little effect on weld strength. However, vibration amplitude and weld time had a significant effect. For vibration amplitudes of 19.09 $\mu m_{p\text{-}p}$ (0.00075 $\text{inches}_{p\text{-}p}$) the weld strength was always low and insufficient melting and fusion occurred. For vibration amplitudes of 35.53 $\mu m_{p\text{-}p}$ (0.0014 $\text{inches}_{p\text{-}p}$) the weld strength was the highest but damage and extensive marking of the fabrics was observed. A vibration amplitude of 27.31 $\mu m_{p\text{-}p}$ (0.0011 $\text{inches}_{p\text{-}p}$) was found to be a good compromise between high weld strength (nearly as high as for the 100% amplitude), with little or no damage to the fabrics.

Reference: Ozaltun H, Benatar A, Nayar SK: Ultrasonic plunge welding of polypropylene nonwovens. ANTEC 2006, Conference proceedings, Society of Plastics Engineers, Charlotte, May 2006.

PP

The size of the HAZ was approximately 120 μm (0.0047 inches) for ultrasonic welds made using the following welding parameters:

- Weld time: 1.5 seconds
- Hold time: 2.0 seconds
- Booster: 2:1
- G-pressure: 275.8 kPa (40 psi)

Reference: Krishnan C, Toussant D, Benatar A: Comparison of weld morphology of polycarbonate and polypropylene for hot plate, vibration and ultrasonic welding. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

PP

Additive type and concentration does have a definite effect on the strength of the ultrasonically welded joints in PP. An increase in part stiffness resulting from the use of additives in the thermoplastic material caused an increase in ultrasonically welded joint strength due to the stiffer materials' increased capacity for transmitting ultrasonic vibration from the horn to the joint interface. As additive concentration levels became very high, there was a drop-off in ultrasonic weld strength, due to less thermoplastic material being at the joint for melting and welding.

The data consistently showed a maximum joint shear strength at approximately 30% additive concentration level for long glass fibers, short glass fibers, and calcium carbonate.

Mineral additives caused the ultrasonically welded joint to have a shear strength equal to, or even somewhat greater than the bulk material, up to an apparent shear strength of 118% of inherent bulk material shear strength at 30% additive concentration level. The reinforcement-type glass additives, on the other hand, appeared to have ultrasonically welded joint shear strength much less than that of the bulk material, with a strength loss of over 50% in the case of 40% long glass-fiber reinforced polypropylene. This effect was to be expected, since reinforced thermoplastics have inherently higher strength than filled thermoplastics, but this reinforcement does not translate across the ultrasonically welded joint interface, leading to strength loss at the joint.

Reference: Carlone MS: Ultrasonic weld shear strength of mineral filled and glass fiber reinforced polypropylene blends. ANTEC 2002, Conference proceedings, Society of Plastics Engineers, San Francisco, May 2002.

Ticona: Celstran PP (reinforcement: long glass fiber)

The recommended welding parameters for ultrasonic spot welding are:

- Sonotrode diameter: 4 mm (0.16 inches)
- Amplitude: 0.05 mm (0.002 inches)
- Ultrasonic exposure time: 1.2 seconds
- Welding pressure: 0.25 MPa (36 psi)
- Holding time: 3 seconds

The achievable tensile shear forces, using the aforementioned conditions are given in Table 35.1.

Reference: *Celstran, Compel Long-Fibre-Reinforced Thermoplastics (LFT),* Supplier design guide, Ticona, 2001.

PP (filler: 20% talc)

A weldability study of painted talc-filled PP was conducted using a 20 kHz ultrasonic plastic joining process. Design of experiments were used to establish a range of baseline welding conditions for unpainted specimens, and then repeated with painted specimens for comparison. Results showed that PP is generally difficult to weld with ultrasonics, even without painted bonding surfaces. However, under certain conditions, ultrasonics can be used to successfully join painted PP thermoplastic resins.

Reference: St John M, Park JB: Ultrasonic weldability of painted plastics. ANTEC 1997, Conference proceedings, Society of Plastics Engineers, Toronto, May 1997.

PP (form: nonwoven filter)

In this application, the welding of nonwoven polypropylene filters, the periphery of a filter was ultrasonically welded to block out contaminants. The problem was consistency, because of inconsistent density in the nonwoven fabric. This density variation is magnified when the part is welded, due to the sharp transition of the material as it melts. The power draw remains fairly constant for most of the process yet rises dramatically at the end of the weld when the material melts. If the weld time extends beyond this point, over welding occurs. If the weld is discontinued prior to this point, no fusion occurs. Thus, a proper weld time has a very narrow range.

When the amplitude was reduced at a preset power level, the slope of the power curve was reduced. This resulted in slowing the process and controlling the melt of the material which created a more robust process and consistent/uniform welds.

Table 35.1. Ultrasonic Spot Welding of Celstran PP

Number of Welding Points	Tensile Shear Force, N (lbf)	
	Upper Sheet Thickness of 3 mm (0.12 inches)	Upper Sheet Thickness of 4 mm (0.16 inches)
1	2800 (630)	3400 (760)
2	4500 (1010)	5200 (1170)
3	6200 (1390)	8200 (1840)

Reference: Grewell DA, Frantz JL: Amplitude control in ultrasonic welding of thermoplastics. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

PP

In order to achieve maximum ultrasonic weld joint strengths in polypropylene, processors should consider the following:

- Welding input parameters optimization needs to be linked directly to part acceptance criteria, whether it be pull or burst strength, hermetic seal integrity, or other factors.
- Reliance on travel distance, weld energy, or time should not be made in order to assume maximum joint strength while trying to optimize the process.
- Maximum joint strengths can be obtained by welding at a primary weld force and then switching to a lower weld force.
- Changing amplitude during the welding cycle either upward or downward, does not have a positive impact on weld strength.
- Precise, closed-loop control over the weld force is critical to weld strength, since minor force changes greatly influence weld strength.

Furthermore, in order to achieve maximum joint strengths in polypropylene, designers need to both incorporate a proper joint design and use a secondary lower weld force.

Reference: Nayar SK, Cavaleri ME, Brostrom M: Morphological changes in ultrasonically welded polypropylene. ANTEC 1993, Conference proceedings , Society of Plastics Engineers, New Orleans, May 1993.

PP

Far-field ultrasonic welding of polypropylene was not successful. The parts melted at the horn/part interface with little or no melting of the energy director. It is suggested that for semicrystalline polymers, the length of the part should be so chosen that the joint interface is at a displacement antinode. This is done by designing the top part to be half a wavelength. This will make far field ultrasonic welding as effective for semicrystalline polymers as it is for amorphous polymers.

Reference: Benatar A, Cheng Z: Far-field ultrasonic welding of thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

PP

Near-field ultrasonic welding of polypropylene was successful. It was generally found that increasing the weld pressure initially increases the weld strength, with further increase in pressure decreasing the strength due to unfavorable molecular alignment. Increasing the weld time increased the energy dissipated and strength; the strength leveled off at weld times greater than 1.5 seconds. Increasing the amplitude of vibration increased the energy dissipated and strength more than with amorphous polymers—with the exception of low amplitudes.

Reference: Benatar A, Eswaran RV: Near-field ultrasonic welding of thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

Doeflex Industries Limited: PP (process type: thermoforming; form: sheet)

Ultrasonic welding should be used for a sheet above 0.5 mm (0.02 inches) thickness.

Polypropylene does not weld as easily as rigid, hard polymers, such as polystyrene, but good results can be achieved if a high amplitude, high energy source is used. However, only close welding is possible, since polypropylene does not transmit ultrasonic waves well enough to allow distant welding.

Reference: *Thermoforming with Polypropylene and Polyethylene,* Supplier data sheets, Doeflex Industries Limited.

PP (features: 5.8 mm (0.228 inches) thick)

Most olefin fibers, woven and nonwoven, have good ultrasonic welding characteristics.

Reference: *Ultrasonic Sealing and Slitting of Synthetic Fabrics,* Supplier technical report, Sonic & Materials, Inc.

35.1.4 Vibration Welding

PP (form: 3.2 mm (0.126 inch) thick injection-molded plaques; filler: talc)

Seven different PP resins for automotive interior applications were selected to evaluate the effects of melt flow rate (MFR) and talc content on weldability.

Results showed that higher melt-down distance and vibration amplitude generated higher weld strength and elongation. For overall weld strength, MFR did not affect the level of weld strength. As the talc content increased, the overall weld strength was decreased significantly. At 30% talc content, the weld strength was 58% less than for material with 13% talc content.

Reference: Park J, Lewis D, Yoon CK: Vibration weldability study for automotive interior application polypropylene. ANTEC 2006, Conference proceedings, Society of Plastics Engineers, Charlotte, May 2006.

Asahi Thermofil: PP (form: 2.5 mm (0.1 inch) thick injection-molded plaques; reinforcement: short glass fiber); **LNP: Verton MFX-7006HS** (form: 2.5 mm (0.1 inch) thick injection-molded plaques, reinforcement: 30% long glass fiber); **LNP: Verton MFX-7008HS** (form: 2.5 mm (0.1 inch) thick injection-molded plaques, reinforcement: 40% long glass fiber)

The target melt-downs of 0.5 mm (0.02 inches) and 2.0 mm (0.08 inches) were used. The weld pressure was varied between 1 and 5 MPa (145–725 psi). The frequency and amplitude (peak-to-peak) were 211 Hz and 1.78 mm (0.070 inches), respectively.

For short-, and long-glass-fiber-reinforced polypropylene compounds, higher fiber content decreased weld strength in the range of 30–40 wt.%. Long-glass-fiber-reinforced polypropylene compounds had generally equal or lower weld strength than short-glass-fiber-reinforced polypropylene compounds. Weld strength of short-glass-fiber-reinforced polypropylene compounds decreased slightly with increasing weld pressure, while the weld strength of long-glass-fiber-reinforced polypropylene compounds increased slightly with increasing weld pressure. Melt-down had little effect on the weld strength for both short-and long-glass-fiber-reinforced polypropylene compounds.

Reference: Dai XY, Bates PJ: Vibration welding short- and long-glass fiber-reinforced polypropylene compounds. ANTEC 2005, Conference proceedings, Society of Plastics Engineers, Boston, May 2005.

PP (form: foam)

A strength virtually equivalent to the base material strength of the foamed material was achieved. Therefore, the reduction in strength due to foaming, that is, the strength of the base material, has a greater influence on the material strength than does the joining pressure on the joint strength. The influence of the amplitude on the weld strength is even smaller than that of the joining pressure. With low amplitudes and low pressures, the welding speed of the base material differs considerably from those of the foamed material. It is therefore important for maximum amplitudes to be used for foamed materials as a matter of principle, in order to guarantee the highest possible energy input and achieve minimum cycle time.

Welding factors of 0.9 and above were attained.

Reference: Potente H, Wilke L: Welding thermoplastic foams. ANTEC 2005, Conference proceedings, Society of Plastics Engineers, Boston, May 2005.

PP

The size of the HAZ was approximately 220 µm (0.0087 inches) for vibration welds made using the following welding parameters:

- Peak-to-peak amplitude: 1.27 mm (0.05 inches)
- Pressure: 206.84 kPa (30 psi)
- Weld time: 4 seconds

Reference: Krishnan C, Toussant D, Benatar A: Comparison of weld morphology of polycarbonate and polypropylene for hot plate, vibration and ultrasonic welding. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

Ticona: Celstran PP (reinforcement: long glass fiber)

Vibration welding gives good values for weld strength. Values up to 25 MPa (3,600 psi) are achieved with Celstran PP under the following conditions:

- Welding pressure: 1 MPa (145 psi)
- Welding time: 5 seconds
- Welding depth: 2.0 mm (0.08 inches)

Reference: *Celstran, Compel Long-Fibre-Reinforced Thermoplastics (LFT),* Supplier design guide, Ticona, 2001.

BASF AG: Novolen 1100 (form: injection-molded plates)

Biaxial vibration welding was carried out using joining pressures between 0.5 and 8.0 MPa (70–1,200 psi). The weld penetration was fixed at 1.5 mm (0.059 inches). Linear and biaxial (elliptic and circular) amplitudes were changed from 0.3 to 0.9 mm (0.012–0.035 inches).

Results showed that the temperature in the interface layer is significantly influenced by the amplitude; an almost linear correlation between amplitude and temperature exists. Generally, the maximum temperature in the interface layer was not more than 20 K (36°F) above the melting temperature of the base material (162°C; 324°F) in linear and biaxial vibration welding.

Joining pressure appeared to have no significant effect on thermal conditions in biaxial vibration welding of polypropylene plates. The viscosity of the polymer is more important, which is easy to understand: for high melt volume rates, less heat is generated in the weld plane.

The influence of pressure itself is the same as in linear vibration welding; mechanical joint quality goes down from weld factors near 1.0 with increasing loads.

Mechanical joint qualities near base material strength are possible with biaxial amplitudes.

Reference: Vetter J, Ehrenstein GW: Biaxial vibration welding of polypropylene. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

PP (form: random long-fiber GMT)

In PP reinforced with random GMT, the fibers are ineffective for reinforcing vibration-welded butt joints. The maximum weld strengths attained with GMT are comparable to the strengths of good welds of the unfilled material. High welding pressures and high amplitudes result in lower mechanical properties. The optimum penetration depends on the fiber content of the bulk material. This penetration dependence is different from that for unfilled thermoplastic, for which the mechanical properties are independent of the penetration, once a steady state has been attained.

Reference: Gehde M, Giese M, Ehrenstein GW: Welding of thermoplastics reinforced with random glass matt. *Polymer Engineering and Science*, 37(4), p. 702, April 1997.

BASF AG: Novolen 1100L

On reaching the steady state phase in the vibration welding process, the mechanical behavior of the weld correlates with three typical structural build-ups. High pressure (3.0 MPa; 435 psi) generates a weld with different appearances in the center and at the edge of the bars. The thickness in the center is about 0.08 mm (0.003 inches), at the edge the weld opens to a delta of about 0.9 mm (0.035 inches). Enlargements show that the joining plane itself is characterized by an optically bright line. This line is attached to a layer whose microstructure could not be defined by microscopy. The transition from this layer to the bulk material is formed by a thin layer of deformed spherulites. For these welds, tensile strength was observed at a welding pressure of 2.0 MPa (290 psi). Microtomed slices showed that the weld is about 0.07 mm (0.003 inches) thick and delta areas (in which the weld opens) are not present. These welds show the following microstructural zones, the joining plane, the inner layer without microstructure, and the transition layer to the bulk material formed by deformed spherulites.

Welds produced with low joining pressure (0.5 MPa; 73 psi) show three microstructural zones: first the inner layer, second, a so-called recrystallized zone with spherulites of different size; the third zone is the transition layer of deformed spherulites. In contrast to the two other types, the thickness of the entire weld is about three times as large. For these welds, the tensile strength was high.

Reference: Giese M, Ehrenstein GW: Studies of the deformation and failure behavior of vibration welded polypropylene welds. ANTEC 1992, Conference proceedings, Society of Plastics Engineers, Detroit, May 1992.

BASF AG: Novolen 1100L

The results of this vibration welding study show that high amplitude and high welding pressure lead to a short welding time. However, in spite of reaching Phase III in the welding cycle (the phase in which a steady state melt is achieved, and the penetration increases linearly with time until vibration stops), the impact strength of the weld is low. The mechanical behavior of the welds can be determined through analysis of the microstructure (Fig. 35.1). Welds with only two layers (inner layer and band of deformed spherulites) with and without delta-shaped areas have unsatisfactory impact strength. Only the welds with three different microstructural layers and a large weld thickness lead to high impact resistance. These welds occur if vibration stops in Phase III with low pressure independent of amplitude.

Reference: Schlarb AK, Ehrenstein GW: The impact strength of butt welded vibration welds related to microstructure and welding history. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, 1989.

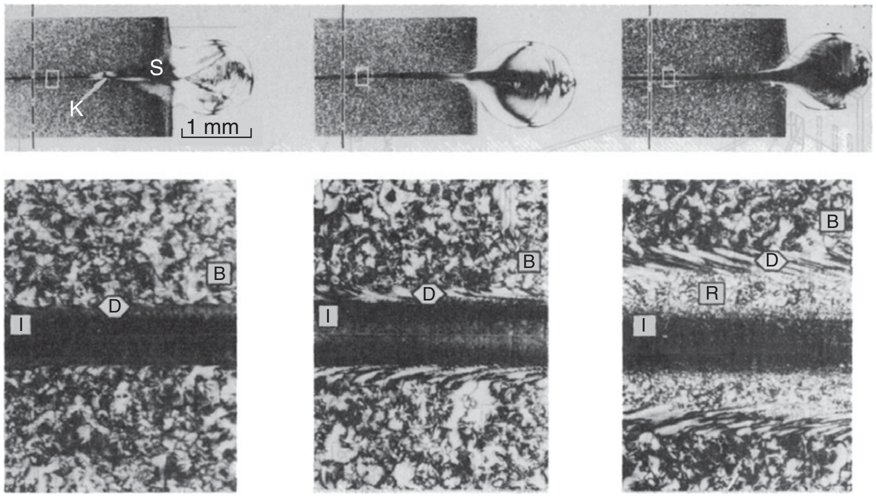


Figure 35.1. Polarization micrographs showing microstructures of three typical vibration welds of a polypropylene homopolymer. Welding pressures are (a) 8.0 MPa (1160 psi) (b) 2.0 MPa (290 psi) (c) 0.5 MPa (73 psi). Weld amplitude is 0.7 mm (0.03 inches). In the upper micrographs, high pressure results in an area of weld thickness of about 50 μm (0.002 inches) gradually increasing in thickness to 1 mm (0.04 inches); high pressure causes the melt flow to change from laminar in the boxed area to turbulent at point K. At lower pressures, this area of greater weld thickness is not present. In the lower micrographs, higher pressure welds (8.0 MPa; 1160 psi, 2.0 MPa; 290 psi) are separated from the bulk material (B) by two zones: an inner layer (I) adjacent to the joining plane and a layer of deformed spherulites (D). Low pressure welds (0.5 MPa; 73 psi) are composed of three zones: an inner layer (I), a middle zone with spherulites of different sizes (R), and a third layer of deformed spherulites (D).

PP

A large American electrical appliance company converted its production line of glass-filled polypropylene dishwasher pump housings from hot plate welding to vibration welding. The change made the operation faster, easier, more energy efficient, and easier to maintain. Control of strength and appearance were also better.

The process is less labor intensive than hot plate welding. With hot plate welding, two welders were needed for three shifts and a third half the time. Leak testing had to be carried out at a separate station after allowing time for parts to cool. In addition, venting systems were needed to eliminate gases generated by the process.

These problems were eliminated by vibration welding. One vibration welder replaced the two hot plate welders. A leak tester attached to the frame of the vibration welder enables the operator to test a part immediately after its assembly and while the next part is being welded. Cooling time is not required because vibration welding does not heat the part. Although pump-housing halves warped from molding, warping in the final product was minimized because the components were clamped under pressure before welding. Cycle time, 30 seconds for the hot plate welder, was reduced to 10 seconds for the vibration welder, including testing.

Design of the pump housing remained unchanged despite the shift from hot plate welding to vibration welding.

In a study on energy consumption, the manufacturer found that the vibration welder required only 2622 kW-hours of electricity per year, compared with 38,000 kW-hours for the hot plate welder which draws power constantly to maintain temperature even when it is not welding. Vibration welding required power only during the weld cycle.

Reference: White P: Vibration welding. *Making It With Plastics*, trade journal, 1987.

35.1.5 Hot Gas Welding

PP (form: sheet)

The following welding conditions are recommended for PP: temperature of 280–330°C (536–626°F), force (for a 4 mm (0.16 inch) diameter welding rod) of 25–35 N (5.6-7.9 lbf) and a gas flow of 40–60 l/minute.

Reference: Gibbesch B: Thermoplastic inliner for dual laminate constructions. Welding Beyond Metal: AWS/DVS conference on Plastics Welding, New Orleans, March 2002.

35.1.6 Laser Welding

PP (filler: 20% talc; form: injection-molded T-piece)

Laser welding trials were carried out between olefin thermoplastic elastomer as a transmission material and talc-reinforced PP as an absorption material. The laser had a wavelength of 940 nm, a power output of 10–50 W, a scanning rate of 10 mm/s (0.39 inches/s) and a spot size of 1.0 mm (0.039 inches) diameter. The welding pressure was 0.4 MPa (58 psi).

Blending a transmitting black colorant into the transmission material generated better welding strength than the case without addition, since it prevents excessive thermal generation in the absorption resin.

Reference: Isoda A, Hatase Y, Nakagawa O, Yushina H: Laser transmission welding of colored thermoplastic elastomers and hard plastics. ANTEC 2006, Conference proceedings, Society of Plastics Engineers, Charlotte, May 2006.

PP

For the experiments, transparent and carbon black pigmented plates were used. They had a thickness of 2 mm (0.079 inches), a length of 78 mm (3.1 inches) and a width of 20 mm (0.79 inches). The overlap was about 10 mm (0.39 inches). The laser beam had a circular focus with a diameter of 2 mm (0.079 inches), and the electric energy and the feed rate were varied to produce line energies between 107 and 759 J/m.

A considerable increase in the maximum short-term tensile force versus line energy can be seen for a storage period of 21 hours compared to 10 minutes. This can be derived from the residual stress caused by the local heating of the laser beam. During storage, relaxation processes are capable of reducing the residual stress, even at ambient temperatures.

Reference: Vetter J, Duriau-Montagne F, Ehrenstein GW, Hänsch D: Morphology and thermal loading in laser welding of thermoplastics. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

PP

Low-power CO_2 lasers have the capability of joining thin (<0.2 mm; 0.008 inches) plastic sheets in lap and cut/seal configurations at high speeds (50 m/min; 165 ft/min) (Table 35.2). Applications could include high-speed packaging where a noncontact, flexible, computer-controlled system would have advantages over ultrasonic, dielectric, and heat-sealing techniques. The Nd:YAG lasers, with the lower absorption capabilities of the shorter wavelength, have the potential to be applied to joining plastics in the thickness range of 0.2–2.0 mm (0.008–0.08 inches) in lap- and butt-joint configurations. Benefits include low distortion and low general heat input. Differences in the melting of the plastic materials and the effect of pigmentation with Nd:YAG lasers have been noted and must be examined further.

Reference: Jones IA, Taylor NS: High speed welding of plastics using lasers. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, 1994.

PP

Under optimum welding conditions, laser welding of polypropylene produces joints with strengths 33.3 ± 0.7 MPa (4,830 ± 100 psi) and elongations equal to the bulk material. In these cases, failure usually occurs outside the weld region. Among the welding parameters studied (power, beam offset from the focal point being on the tip surface of the specimen, shielding gas flow rate, welding pressure, and travel speed), laser beam offset (power density) and welding pressure showed the most significant effect on the joint strength. Increasing the beam offset while decreasing power density increased the joint strength all the way to the highest offset tested. For PP, there existed an optimum pressure for achieving the highest joint strength. The effect of power, travel speed, and shielding gas flow rate on joint strength was very small as long as the interface could be

Table 35.2. Summary of Laser Weld Conditions and Tensile Properties for Polypropylene Joints

Material			Laser Conditions			Tensile Properties	
Type	Thickness, mm (inches)	Joint Type	Type	Power, W	Speed, m/min (ft/min)	Percentage of Parent	Failure Mode
PP	0.2 (0.008)	Lap	CO_2	100	51 (167)	98	Parent
PP	0.2 (0.008)	Lap	Nd:YAG	80	0.2 (0.7)	70	Weld
PP	0.2 (0.08)	Butt	Nd:YAG	80	0.1 (0.3)	30	Weld

cut in one pass. Generally, laser welding of PP was very fast and required no prewelding preparations.

Reference: Ou BS, Benatar A, Albright CW: Laser welding of polyethylene and polypropylene plates. ANTEC 1992, Conference proceedings, Society of Plastics Engineers, Detroit, 1992.

35.1.7 Infrared Welding

PP (form: pressure tank; reinforcement: glass fiber)

Infrared welding has been used to produce a joint in a composite pressure tank that is significantly stronger than the parent cylinder body, which is made of glass-fiber reinforced polypropylene.

The heart of the welding machine is an arrangement of four banks of six, short-wave infrared emitters (1.6 kW), which are clamped and spring-loaded on either side of a movable platen. In operation, two bottom cylinder halves, each of 140 mm (5.5 inches) diameter, are loaded into the machine and then two matching top cylinder halves are located in position and held under suction directly above the bottom halves.

When the start button is pressed manually, all four cylinder halves are firmly clamped, the movable platen is advanced to its working position between the butt ends of the opposing cylinders, and the power is switched on. The infrared emitter then exposes the opposing butt ends to infrared heat for around 40 seconds, until the melt temperature is achieved, and the facing circumferences of the cylinders are softened. The platen is then withdrawn, the power is switched off, and the butt ends are brought together under pressure to effect the weld.

The weld strength achieved by the infrared technique has proved so good that under bursting tests at pressures of around 2800 kPa (28 bar; 406 psi), it has been found that the cylinder body has been destroyed well before the welded joint.

Reference: Bartley I: Infra-red welding. *Advanced Composites Bulletin,* p. 8, July 2001.

PP

The effect of welding parameters on noncontact hot plate butt welding of polypropylene was investigated. For a given hot plate temperature, an optimum heating time and forging pressure was found. Increasing or decreasing the heating time and/or pressure from the optimum value resulted in a lower joint strength. Increasing the forging time improved the joint strength. A "push and pull" technique was applied during the forging stage to reduce adverse molecular orientation. This consisted of applying a push force of around 200 N (45 lbf) for 1 second, followed by a "pull" stage which consists of reducing the welding force to zero.

Reference: Lin TT, Staicovici S, Benatar A: Non-contact hot plate welding of polypropylene. ANTEC 1996, Conference proceedings, Society of Plastics Engineers, Indianapolis, May 1996.

PP

IR welding is faster than hot plate welding, and it produces joint strengths that are equal to the bulk strength. For hot plate welding using a heating time of 40 seconds, a changeover time of 0.5 second, and a weld time of 40 seconds, the joint strength was 85% of the bulk strength. For IR welding with a heating time of 11 seconds, changeover time of 0.8 seconds, and a hold time of 11 seconds, the joint strength was equal to the bulk strength (33 MPa; 4,800 psi). Therefore, for IR welding the total cycle time was only 23 seconds, compared with 80 seconds for hot plate welding.

There are optimal heating times and pressures to achieve the highest joint strengths. Reducing or increasing the heating time and welding pressure from optimum decreases the weld strength. For optimal welding, the changeover time should be kept as short as possible. Increasing the heating distance has the effect of decreasing the energy density at the surface, thereby lengthening the cycle time. The microstructure that develops in the weld zone is similar to that observed in hot plate welding. It can be divided into three regions, a bulk material region, a flow region, and a region of small spherulites at the weld center. In general, IR welding produces excellent joints with very short cycle times.

Reference: Chen YS, Benatar A: Infrared welding of polypropylene. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

PP

Experiments have shown that a range of welding parameters can be used to reach the maximum weld quality, with the melt depth and joining distance being the determining parameters. The melt depth is fixed by the energy going into the joint, and this is a function of: nature of heater, temperature, exposure time, geometry of the welding assembly, and the polymer to be melted.

The mechanical testing conducted on the high-quality infrared welds has shown that the welding factors achieved for polypropylene when tested at –40°C (–40°F) were greater than 0.9.

Reference: Taylor NS, Klaiber F, Wermelinger J: Assessment of PP and PVDF joints made by a new infrared jointing system. ANTEC 1993, Conference proceedings, Society of Plastics Engineers, New Orleans, May 1993.

35.1.8 Resistive Implant Welding

Himont: PP (reinforcement: glass fiber)

The suitability of using resistance heated fusion bonding to join glass-reinforced polypropylene (GRPP) was demonstrated. C-scans and micrographs of the welded regions showed uniformity throughout the majority of bond areas, which represented a variety of process conditions. Shear strengths of 17.0 MPa (2470 psi) were obtained, with process times of less than two minutes.

The fundamental process–performance relationships were established for resistance welded GRPP joints. Relatively low pressures, temperatures, power levels, and process times will yield strong bonds, even with little or no adhesion between the heating element (expanded stainless steel foil) and the polymer. The relationship between processing and performance could be inferred from the lap shear data. Temperatures 10–15% above the melt temperature coupled with low power and pressure, and short dwell times are conducive to uniform welds, as the C-scans and optical micrographs revealed. In the single lap configuration, these processing conditions were sufficient to promote failure into the bulk adherends away from the interface. The shore beam shear tests reinforced this observation. Also, the treatment of the heating element was revealed to be of critical importance.

Reference: McBride MG, McKnight SH, Gillespie JW: Joining of short fiber glass reinforced polypropylene using resistance heated fusion bonding. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

35.1.9 Induction Welding

PP (material composition: 40% glass mat)

A 40% glass mat composite (GMT) with a polypropylene matrix is used to produce structural load floors for station wagons (Fig. 35.2). Initially, the GMT material replaced stamped steel which offered decreases in weight and less noise under vibration testing than the steel load floors. The load floor had to withstand a static load of 2.107 kg/m^2 at 82.2°C (180°F) without deflecting more than one inch. The finished component also had to withstand a 15° torque test without bond failure. In order to meet these requirements, continuous welding of the two halves was necessary.

The use of EMA compound at the interface of the flat panel and the ribbed shell was critical in attaining the necessary structural weld. Since polypropylene is added to the weld interface, the difficulties associated with the high glass content of the GMT were overcome. The EMA material actually bonds to the glass and welds to the surrounding polypropylene matrix. As the EMA material melts and flows under pressure, the surface irregularities are filled. The resultant weld provides a uniform structural weld between the two mating parts.

Polypropylene is perhaps the easiest thermoplastic material for the EMA process to weld together. The EMA process is currently used for a number of polypropylene applications. One specific application welds a two-piece polypropylene tea kettle unit together. The EMA process was selected for this particular application for a number of reasons. Aesthetics played a key role in the decision to use the EMA process. The EMA process provides better aesthetics and part fit than the hot plate approach. This is achieved through the standard practice of using a completely contained joint. The fixturing utilized with the EMA process provides exact part alignment 100% of the time. Obviously, reliability is critical to this type of application. The EMA process provides for near 100% repeatability and near 100% leak proof reliability. The EMA process also provides for a fast cycle time, in this case, 11 seconds.

Reference: Chookazian SM: Electromagnetic welding of thermoplastics and specific design criteria with emphasis on polypropylene. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

Solvay: Fortilene

Electromagnetic welding lends itself well to automation and produces structural, hermetic, or high pressure welds. The process works well for polypropylene and offers several advantages:

- The size of the bond can vary from a small spot to a long, continuous weld.
- Irregular bond surfaces due to mold or heat shrinkage, for example, do not affect the weld.
- The bond area need not be symmetrical.

Reference: *Fortilene Polypropylene Properties, Processing, and Design Manual,* Supplier design guide, Soltex, 1981.

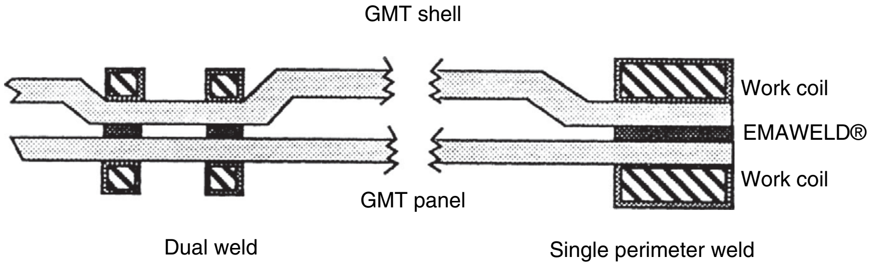


Figure 35.2. 40% glass mat composite with a polypropylene matrix structural load floor for station wagons.

35.1.10 Heat Sealing

Toyobo: PP (form: 20 µm (0.0008 inch) thick oriented and 25 µm (0.001 inch) thick cast film, laminated)

The plastic films used in this study were oriented polypropylene (OPP) and cast polypropylene (CPP). The heat-sealing temperature was observed to rise within a very short period to the set temperature. It was maintained briefly for 0.1 seconds. Then it cooled to room temperature in 5.0 seconds. The pressure was kept at 0.42 MPa (61 psi) throughout the heat-sealing procedure. The width of the heat-sealing part was 10 mm (0.39 inches). 180° peel tests were conducted at a crosshead speed of 1 mm/min (0.04 inches/min) with a 50 mm (2 inch) gauge length. Peel tests under creep loading were also carried out under applied loads of 14.7, 13.7, and 12.8 N (3.3, 3.1, and 2.9 lbf) in the vertical direction, and the time to fracture of the specimen was measured.

Static peel strength of the heat-sealed parts was independent of the film direction, that is, machine (MD) or transverse (TD). The specimen heat sealed at 170°C (338°F) showed slightly higher static peel strength than that at 130°C (266°F) and 150°C (302°F). Under creep loading, TD specimens heat sealed at 170°C (338°F) showed the highest creep property among all the tested specimens.

Reference: Nishikawa Y, Fujita Y, Pivsa-Art S, Nakai A, Kotaki M, Hamada H: Fracture behavior of heat-sealed PP films under static and creep loadings. ANTEC 2006, Conference proceedings, Society of Plastics Engineers, Charlotte, May 2006.

PP (form: 20 µm (0.0008 inch) thick oriented and 25 µm (0.001 inch) thick cast film, laminated)

Failure criteria of the heat sealed part of oriented polypropylene (OPP) and cast polypropylene (CPP) heat seals made by an impulse type heat-sealing machine were investigated. During the sealing process, the temperature was observed to rise within a very short period to the set temperature, at which it was maintained briefly for 0.1 seconds. It then cooled to room temperature in 5.0 seconds.

The notched strength as a function of heat-sealing temperature revealed that the seals were stronger in the transverse direction (TD), which is the orientation direction, compared to the machine direction (MD). Mechanical properties maintained consistently minimum values at high sealing temperatures, in tandem with the loss of orientation of the OPP film. The weakest part was identified as the immediate neighborhood outside the heat seal.

Reference: Ishiaku US, Hashimoto Y, Tetsuya T, Hamada H: Effect of heat sealing temperature on the fracture aspects of OPP/CPP seal. ANTEC 2005, Conference proceedings, Society of Plastics Engineers, Boston, May 2005.

Doeflex Industries: PP (process type: thermoforming; form: sheet)

It is sometimes required that a clear window be attached to a polypropylene binder, and the ideal fixing method is heated tool welding.

Polypropylene film with a thickness of between 150 and 250 µm (0.006-0.010 inches) is generally used, together with a heated brass tool supported in a simple press. Temperature, time, and pressure should be adjusted to give a good seal without causing excessive flow. Heated tool welding is very slow for a sheet above 0.5 mm (0.020 inches).

For fixing a small window, hand pressure, temperatures of 150–180°C (302–356°F) and times of 2–5 seconds have been found satisfactory.

Reference: *Thermoforming with Polypropylene and Polyethylene,* Supplier data sheets, Doeflex Industries Limited.

35.1.11 Friction Stir Welding

PP (form: 6 mm (0.24 inch) thick stress-relieved extruded sheet)

Friction stir welding trials were carried out using a heated shoe. This gives the system sufficient thermal energy to fully form a welded joint.

Results showed that to achieve minimal disruption of polymer microstructure, welds should be made at a low feed rate (5–10 cm/min; 2-4 inches/min), a high shoe temperature (>160°C; 320°F), a long pressure time (>90 seconds) and a large pin diameter (9 mm; 0.35 inches). A properly executed weld will have the following characteristics:

- The spherulite size and orientation will be the same in the weld as in the base material.
- No distinct flow lines or swirl marks will exist in the weld zone.
- There will be a narrow region of altered spherulite orientation at the weld/base material boundary.

If these characteristics are present, the microstructure of the weld region will closely approximate to that of the base material, and any applied stresses will be most efficiently transferred.

Reference: Strand S, Sorensen CD, Nelson TW: Effects of friction stir welding on polymer microstructure. ANTEC 2003, Conference proceedings, Society of Plastics Engineers, Nashville, May 2003.

PP

Friction stir welding of PP has been demonstrated to be a viable joining process, with tensile strengths of 98% of the base material strength.

A special tool with a fixed shoe, rather than a rotating shoulder, is necessary to successfully weld thermoplastics. The shoe should have a controllable temperature to optimize the FSW process. Tools with smooth pins are unacceptable. Threaded tools with both straight and tapered pins appear to work well.

The machine spindle speed appears to be the most significant process parameter for FSW of thermoplastics.

Reference: Sorensen CD, Nelson TW, Strand S, Johns C, Christensen J: Joining of thermoplastics with friction stir welding. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

35.1.12 Adhesive Bonding

PP

A study was performed on the effect of vacuum plasma pretreatment with respect to adhesive bond strength on PP. Two types of high-strength epoxy adhesives were used: Eccobond® 2332 (a single-component adhesive) and Eccobond® 45W1 (a two-component adhesive). Eccobond® 2332 was cured for 1 hour at 120°C (248°F), Eccobond® 45W1 was used in a 1:1 ratio with Catalyst 15 and was cured for 24 hours at room temperature. The plasma-treated samples were glued together within one day of the plasma treatment.

Results showed that vacuum plasma pretreated samples had a tenfold increase in bond strength, compared with untreated samples.

Reference: Lippens P: Vacuum plasma pre-treatment enhances adhesive bonding of plastics in an environmentally friendly and cost effective way. Joining Plastics 2006, Conference proceedings, London, UK, April 2006.

Himont: Profax 6323

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125” (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 35.3 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 35.3, so the effect

Table 35.3. Shear Strengths of Profax PP to PP Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[a]

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	5 rms	50 (0.3)	50 (0.3)	>1950[b] (>13.5)[b]	50 (0.3)	200 (1.4)	100 (0.7)
Roughened	26 rms	50 (0.3)	1950 (13.5)	1300 (9.0)	300 (2.1)	200 (1.4)	450 (3.1)
Antioxidant	0.1% Irganox 1010; 0.3% Cyanox STDP	50 (0.3)	1950 (13.5)	>1950[b] (>13.5)[b]	50 (0.3)	200 (1.4)	100 (0.7)
UV stabilizer	0.5% Cyasorb UV 531	50 (0.3)	50 (0.3)	>1950[b] (>13.5)[b]	50 (0.3)	200 (1.4)	100 (0.7)
Impact modifier	9% Novalene EPDM	50 (0.3)	1350 (9.3)	>1950[b] (>13.5)[b]	200 (1.4)	200 (1.4)	100 (0.7)
Flame retardant	9% PE-68; 4% Antimony oxide	50 (0.3)	50 (0.3)	>1950[b] (>13.5)[b]	50 (0.3)	200 (1.4)	250 (1.7)
Smoke suppressant	13% Firebrake ZB	50 (0.3)	50 (0.3)	>1950[b] (>13.5)[b]	50 (0.3)	200 (1.4)	100 (0.7)
Lubricant	0.1% Calcium stearate 24-26	50 (0.3)	50 (0.3)	>1950[b] (>13.5)[b]	50 (0.3)	200 (1.4)	100 (0.7)
Filler	20% Cimpact 600 Talc	50 (0.3)	50 (0.3)	>1950[b] (>13.5)[b]	100 (0.7)	200 (1.4)	100 (0.7)
Colorant	0.1% Watchung Red RT-428-D	50 (0.3)	50 (0.3)	>1950[b] (>13.5)[b]	50 (0.3)	200 (1.4)	100 (0.7)
Antistatic	0.2% Armostat 475	50 (0.3)	200 (1.4)	>1950[b] (>13.5)[b]	200 (1.4)	200 (1.4)	100 (0.7)

[a] All testing was done according to the block shear method (ASTM D4501).Values are given in psi and MPa (within parentheses).

[b] Due to the severe deformation of the block shear specimens, testing was stopped before the actual bond strength achieved by the adhesive could be determined (the adhesive bond never failed).

of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 instant adhesive, used in conjunction with Prism Primer 770, achieved the highest bond strengths on PP, typically substrate failure. Loctite 3030 adhesive (a polyolefin bonding adhesive) achieved comparable strength, but no substrate failure. Hysol 3651 hot melt adhesive (polyolefin based) had the third highest strength. All other adhesives tested performed poorly on unprimed, un-abraded PP.

Surface Treatments: The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, resulted in a dramatic, statistically significant increase in the bond strengths achieved on PP, typically substrate failure. Surface roughening resulted in either no effect, or a statistically significant increase in the bond strengths achieved on PP.

Other Information: Polypropylene is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4,* Supplier design guide, Loctite Corporation, 2006.

PP

Polypropylene can be bonded using anaerobic, cyanoacrylate, UV, epoxy, and structural acrylic adhesives. For cyanoacrylate adhesive, use Permabond POP primer. For other adhesives, surface treat via flame, corona, or plasma treatment equipment.

Reference: *The Engineers Guide to Adhesives,* Supplier design guide, Permabond Engineering Adhesives.

Hoechst AG: Hostacom (reinforcement: glass fiber)

Because of the high chemical resistance of Hostacom's PP matrix, no surface attack takes place at room temperature on molded parts in contact with solvents so that—unless the surface is pretreated—only pressure-sensitive adhesives can be used. Surface pretreatment brings about a considerable improvement in joint strength. It can be carried out in various ways:

- A primer (for example Herberts R 47 509)
- Flame treatment with a very oxygen-rich burner flame
- Electrical surface discharge treatment (corona)
- Dipping in a chromosulfuric acid bath

Suitable adhesive systems for bonding parts made from Hostacom polypropylene are given in Table 35.4.

Reference: *Hostacom Reinforced Polypropylene,* Supplier design guide (B115BRE9072/046), Hoechst AG, 1992.

35.1.13 Mechanical Fastening

PP (reinforcement: 40% long glass fiber)

The total cycle time of hot air sticking is longer than ultrasonic riveting. Hot air sticking takes approximately 30 seconds, compared to 15 seconds for ultrasonic riveting. Both techniques had similar joining forces (<1000 N; 225 lbf). Hot air sticking joints showed a 50–90% better load-bearing performance than ultrasonic riveting joints resulting from the fiber preserving forming operation.

Reference: Hahn O, Finkeldey C: Ultrasonic riveting and hot-air-sticking of fibre-reinforced thermoplastics. ANTEC 2002, Conference proceedings, Society of Plastics Engineers, San Francisco, May 2002.

Shell Chemical: Shell KM6100

The purpose of this study was to answer one question: How does time lapse affect the holding power of molded-in threaded brass inserts in polypropylene? To answer the question, samples were injection molded with inserts and tested in tension after 1, 10, 50, 100, 200, 500, and 1000 hours.

The results indicated that the pull-out resistance increased as the time increased (from 2110 N (474 lbf) for 1 hour to 2435 N (547 lbf) for 1000 hours). At lower times, the changes were greatest and, as the time lapse increased, the changes in pull-out resistance became less. It might be expected that the resistance would increase to some point, and then level off. However, at 1000 hours, the data did not indicate a clear point of

Table 35.4. Adhesive Systems for Bonding Parts Made from Hostacom Polypropylene

Type of Adhesive	Basis
Pressure-sensitive adhesives	Pressure-sensitive adhesive solutions
	Pressure-sensitive adhesive dispersions
Contact adhesives	Synthetic rubber, polyurethane
Two-pack adhesives	Epoxy resin, polyurethane, phenolic resin/synthetic rubber
Hot-melt adhesives	Vinyl copolymers

inflection. The effects of shrinkage continue for extended periods of time. This might shed some doubt on the utility of a uniform 40-hour wait between molding and testing, as is common in several ASTM tests.

Reference: Lokensgard E: Time lapse effects on pull-out resistance of threaded inserts in polypropylene. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

35.2 Polypropylene Homopolymer

35.2.1 Heated Tool Welding

PP Homopolymer (form: pipe)

The recommended socket fusion welding parameters for PP-H pipes are given in Table 35.5.

The temperature of the heated tool should be 250-270°C (482-518°F).

Reference: Frank T: Heated tool welding of thermoplastic pipes (example polyolefins). AWS/DVS conference on Plastics Welding, Orlando, October 2000.

ICI: GWM22 (form: injection-molded ISO-type tensile test bars)

The following hot plate welding conditions were used:

- Hot plate temperature, T: 190-290°C (374–554°F)
- Heating time, t: 20–100 seconds
- Weld displacement, d: 0.35–1.0 mm (0.014–0.039 inches)

The melted zone depth (L_0) was determined by measuring the distance between the outer surface of the bar and the row of small spherulites that limit the recrystallized region.

The properties of the welds reached their maximum for values of melt displacement, RMD (= d/L_0), in the range from 0.38 to 0.75. The weld quality was also affected by the interface temperature; for the set of welds studied in this work, better performance was obtained for the conditions T = 240°C (464°F), t = 50 seconds, d = 0.35 mm (0.014 inches) and T = 265°C (509°F), t = 20 seconds, d = 0.35 mm (0.014 inches).

Reference: Oliveira MJ, Bernardo CA, Hemsley DA: Morphology and mechanical behaviour of polypropylene hot plate welds. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

PP Homopolymer (form: 12 × 0.6 mm (0.47 × 0.024 inch) strapping tape)

The tapes were welded using a semiautomatic strapping machine at temperatures of between 340 and 490°C (644–914°F). The complete welding cycle was 1.4 seconds.

Results showed that the welding temperature had a strong influence on the properties of the welds. An optimum welding tool temperature around 430°C (806°F) could be defined for most of the tapes. The microstructure of the welds was, in general, very fine

Table 35.5. Recommended Heating and Cooling Times for Socket Fusion Welding of PP-H

Pipe Outside Diameter, in.	Heating Time, s		Maximum Change-Over Time, s	Cooling Time	
	SDR11	SDR17.6		Fixed, s	Total, mins
3/8	5		4	6	2
½	5		4	6	2
¾	7		4	10	2
1	8		6	10	4
1¼	12		6	20	4
1½	12		6	20	4
2	24	10	8	30	6
2½	30	15	8	30	6
3	40	22	8	40	6
4	50	30	10	50	8
4½	60	35	10	60	8

SDR: standard dimension ratio = outside diameter/wall thickness.

and showed a much lower orientation than the tapes. Welding temperatures of 460°C (860°F) or higher produced coarser textures and favored the occurrence of voids and splits at the joints.

The welding temperature influenced the fracture path of the welds. Below the optimum temperature, the fracture ran along one of the interfaces; at the optimum range, it alternated between the two interfaces, and above the optimum temperature, it generally moved away from the weld zone.

The orientation of the tapes influenced the morphology of the welds. The increase in orientation reduced the thickness of the weld zone and favored the formation of voids. The welding efficiency decreased with increasing orientation of the tapes.

Reference: Oliveira MJ, Hemsley DA: Orientation effects on the weldability of polypropylene strapping tape. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

35.2.2 Ultrasonic Welding

Montell: 6323 (form: injection-molded AWS ultrasonic welding test specimens; reinforcement: $CaCO_3$, talc, mica, glass fiber)

The objective of this work was to study the differences in the ultrasonic weld strength of polypropylene compounds with different fillers.

The welding parameters were optimized for unfilled PP samples. The weld time had the greatest effect on the weld strength. As the weld time increased, the strength increased up to a plateau, after which further increases in time did not raise the strength or perhaps lowered it slightly. The optimum weld time for unfilled PP was 0.25 seconds. The weld force increased the weld strength of unfilled PP to a plateau at a weld force of 240 N (54 lbf), after which further increases did not increase the strength. The trigger force had almost no effect on the weld strength. Increasing the amplitude resulted in increased weld strength for unfilled PP.

The highest weld strengths were seen for unfilled PP, followed by $CaCO_3$-filled and glass-filled compounds. The talc-filled and mica-filled compounds exhibited the lowest weld strengths. This was attributed to the possibly acquired orientation of the plate-like particles in the direction parallel to the weld plane. This interfered with the diffusion of polymer chains across the weld interface.

The addition of fillers to PP affected the weld strength and elongation at break. With each filler type, increasing the filler level generally reduced the weld strength and elongation. The decrease in the weld strength seen with an increased filler concentration was attributed to the lower polymer volume fraction available for welding at the interface. The filler particles prevented PP from bonding to itself. A decrease in the elongation with filler addition was found in the tensile testing of both the bulk and welded specimens. This was due to the acquired brittle nature of the compounds as the filler level was increased. The highest weld strengths were generally seen for the specimens exhibiting the greatest elongation.

Reference: Sancaktar E, Walker E: Effects of calcium carbonate, talc, mica, and glass-fiber fillers on the ultrasonic weld strength of polypropylene. *Journal of Applied Polymer Science,* 94(5), p. 1986, December 2004.

35.2.3 Vibration Welding

Basell: Pro-fax 6331 (form: 3.2 mm (0.126 inch) thick injection-molded plaques; reinforcement: organoclay)

PP homopolymer was compounded with 0, 3, and 6 wt.% organoclay. Plaques of thickness of 3.2 mm (0.126 inches) were machined into plates of dimensions 50 × 100 mm (2 x 4 inches), which were welded at a frequency of 211 Hz and a peak-to-peak amplitude of 1.8 mm (0.071 inches). The weld pressure was varied from 1 to 4 MPa (145–580 psi) and the target melt-down was varied from 1 to 3 mm (0.04-0.12 inches).

Results showed that the addition of organoclay material to PP matrices causes large drops in weld strength. The weld tensile strength was observed to decrease approximately 25% for each 3% of organoclay added. This is believed to be caused by alignment of the clay platelets at the weld. Relative to this organoclay level effect, the effects of welding conditions on weld strength is small. Four-fold increases in melt pressure caused a 10% increase in weld strength. No significant effect of melt-down was observed.

Reference: Bates PJ, Braybrook C, Kisway T, Tucker B, Gopakumar TG, Pagé DJYS, Wu CY: Vibration welding polypropylene-based nanocomposites. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

35.2.4 Extrusion Welding

PP Homopolymer (form: sheet)

On the basis of the results of the tests made on 10 and 20 mm (0.39 and 0.79 inch) thick butt joints and

T-joints, as well as carrying out an investigation into the mechanical properties of such joints, the optimal parameters for the extrusion welding of PP-H are: a plasticizing temperature for the filler material of 240°C (464°F), an air temperature for the plasticization of the weld groove of 250–275°C (482–527°F), and a feed rate of 3 mm (0.118 inch) diameter filler rod of 222–335 cm/minute (7.28-11.00 ft/minute).

To produce satisfactory joints, bevelling of the sheet to be welded is necessary and should be carried out in such a way that the angle of the welding groove is 90°. The shape and dimensions of the forming overlay should be compatible with those of the welding groove.

The 20 mm (0.79 inch) thick polypropylene butt joints contained uniformly distributed voids in the central parts of their welds. These extended along the whole length of the weld and were thought to be partly due to the strong, secondary shrinkage of the material.

Reference: Dziuba S, Boron S: The technology of extrusion-fusion welding of polythene and polypropylene butt and T joints. *Welding International,* 14(9), p. 677, 2000.

Vestolen P9022 (features: extruded 10 mm (0.39 inch) thick sheet)

The granulate for the weld seam extrusions and the sheet materials were taken from the same production lots. The extrusion welding processing window is given in Table 35.6.

Reference: Jaussent V, Ehrenstein GW: Extrusion welds of different types of polypropylene. *Schweissen und Schneiden,* 50(10), p. 656, October 1998.

PP Homopolymer

The extrusion welding experiments described here were performed with a semiautomatic extrusion welding machine specifically designed to avoid any influence by the operator. During the experiments, the following parameters were measured continuously:

Table 35.6. Processing Window for Extrusion Welding of Polypropylene Homopolymer

Welding Speed, mm/s (inches/s)	Hot Gas Temperature, °C (°F)	
	Minimum	Maximum
4 (0.16)	260 (500)	330 (626)
8 (0.31)	280 (536)	370 (698)

- Revolutions of the extruder screw
- Temperature of the heater bands
- Temperature and pressure of the extrudate
- Hot air temperature in the nozzle
- Welding length and time
- Horizontal and vertical forces at the welding shoe

Results showed that with the temperature of the extrudate at 205–225°C (401–437°F), the main influencing parameters are welding velocity and preheat air temperature. The parameters are limited by reaching a minimum thickness of the recrystallized layer on one hand, and by degradation of the material on the other.

Reference: Gehde M: Extrusion welding of polypropylene. *Welding in the World,* 39(5), p. 279, 1997.

PP Homopolymer (form: 20 mm (0.79 inch) thick sheet)

The relaxation of the residual stresses is mainly influenced by the welding parameters rather than by the seam geometry. With high preheating temperatures (320°C; 608°F) the stress reduction takes place more quickly, which was attributed to the fact that the recrystallization layer is less oriented. By increasing the ambient temperature, the viscoelastic component of the relaxation is markedly accelerated. On the viscous component, on the other hand, no difference could be found during the test period of one month compared with the relaxation at room temperature. Since, essentially, only the viscoelastic component contributes to stress reduction during technically representative times, hot storage can be restricted to relatively short times of less than one week.

Reference: Viertel A, Ehrenstein GW: Relaxation behaviour of polypropylene extrusion welds. *Schweissen und Schneiden,* 49, p. 348, 1997.

PP Homopolymer (features: 10 mm (0.39 inch) thick extruded sheet)

Welded joints were produced on an automatic extrusion welding machine in order to exclude manual influences, and to ensure reproducibility of the results. The hot gas temperature was varied between 200 and 440°C (392–824°F) and the welding speeds were 4 and 8 mm/s (0.16 and 0.31 inches/s). The mass flow of extrudate was matched to the welding speed in order to obtain comparable weld geometries.

Results showed that the welding parameter range within which good short-term properties are reached is narrower than the range for good long-term strength. The plateau of the long-term performance starts from a recrystallized layer thickness of approximately 0.3 mm (0.012 inches), uniformly good short-term parameters, however, only start from a layer thickness of 0.6 mm (0.024 inches).

Above a certain minimum strength of the joining planes, the lifetime of the welded joints depends only on the extent to which the weld is formed free of notches; macroscopic and microscopic notches clearly reduce the weld lifetime.

Reference: Gehde M, Ehrenstein GW: Long-term and failure behaviour of extrusion welded joints. *Schweissen und Schneiden,* 48, p. 280, 1996.

35.2.5 Mechanical Fastening

Shell Chemical: Shell KM6100

The purpose of this study was to answer two questions concerning the pull-out resistance of molded-in threaded brass inserts in polypropylene. How sensitive is the pull-out resistance of molded-in threaded inserts to changes in processing conditions? And do internal lubricants significantly reduce the holding power of molded-in threaded inserts?

The base resin was polypropylene homopolymer, natural, Shell KM6100. Control processing conditions were: nozzle temperature—200°C (392°F), front zone—200°C (392°F), rear zone—150°C (302°F), injection time—10 seconds, injection speed—maximum, cooling time—25 seconds, injection pressure—34.5 MPa (5000 psi), mold cool—18°C (64°F), and insert temperature—22°C (72°F). In addition to the base resin, the effect of compounding the polypropylene with three different lubricants was evaluated, including 1% Epolene wax (low molecular weight polyethylene); 0.3% calcium stearate, and 0.25% Mold Wiz internal lubricant, INT-33A manufactured by Axel Plastics Research Labs, Inc.

The holding power for the control group was 183.5 kgf (405 lbf). Increasing the injection pressure to 69.0 MPa (10,000 psi) decreased pull-out resistance by 13.5 kgf (29.8 lbf). Decreasing pressure to 14.5 MPa (2100 psi) decreased holding power by 18.0 kgf (39.7 lbf). Increasing injection time to 20 seconds reduced holding power by 6.0 kgf (13.2 lbf), while decreasing injection time to 2 seconds reduced holding power by 18.0 kgf (39.7 lbf). These significant effects were due to under- and over-pressurization, and under- and over-packing. Increasing the insert temperature to 95°C (203°F) reduced holding power by 19 kgf (42 lbf). These results indicate that the pull-out resistance of the inserts was sensitive to the selected changes in pressure, injection time, and insert temperature.

Both epolene wax and calcium stearate caused a highly significant reduction in pull-out resistance, lowering it by 29 kgf (64 lbf) and 37 kgf (82 lbf), respectively. The lubricants caused the inserts to slip more easily from the surrounding plastic. The decrease in pull-out resistance caused by the Mold Wiz material was only 9.5 kgf (21 lbf).

Reference: Lokensgard E: Effects of process conditions and internal lubricants on the pull-out resistance of threaded inserts in polypropylene. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

35.3 Polypropylene Copolymer

35.3.1 Heated Tool Welding

PP Copolymer (form: pipe; chemical type: random copolymer)

The recommended socket fusion welding parameters for PP random copolymer pipes are given in Table 35.7.

The temperature of the heated tool should be 250–270°C (482–518°F).

Reference: Frank T: Heated tool welding of thermoplastic pipes (example polyolefins). AWS/DVS Conference on Plastics Welding, Orlando, October 2000.

Hoechst AG: Hostalen (chemical type: copolymer)

In the hot plate weld, spherulites were visible within the weld, and there was a visible HAZ of deformed spherulites separating the weld from the adjacent parent. Differential scanning calorimetry (DSC) results showed that the crystalline structure of the parent polymer had been affected by the welding conditions, and the main effect was the almost complete disappearance of the beta-crystalline form within the weld.

The welds had inferior mechanical properties to those of the sheet from which the samples were taken. The impact strengths of the weld were 24% of the parent material strength. It is possible that the low impact strengths could be due, in part, to the abrupt changes in visible microstructure between the weld and the parent.

Reference: Stevens SM: The effect of welding on the α- and β- crystalline forms of polypropylene. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

Table 35.7. Recommended Heating and Cooling Times for Socket Fusion Welding of PP-R

Pipe Outside diameter, in.	Heating Time, s		Maximum Change-Over Time, s	Cooling Time	
	SDR11	SDR17.6		Fixed, s	Total, min
3/8	5		4	6	2
½	5		4	6	2
¾	7		4	10	2
1	8		6	10	4
1¼	12		6	20	4
1½	12		6	20	4
2	24	10	8	30	6
2½	30	15	8	30	6
3	40	22	8	40	6
4	50	30	10	50	8
4½	60	35	10	60	8

SDR: standard dimension ratio = outside diameter/wall thickness.

PP Copolymer (chemical type: random ethylene copolymers; material composition: 0.5% carbon black)

Hot plate welds made using standard (material manufacturer recommendations) and nonstandard (to study the effect of increased plate removal time) conditions could be distinguished in terms of structural and morphological behavior, but not always on the basis of tensile strength (Table 35.8). Poor tensile strengths were associated with the lack of a region of deformed spherulites at the weld/pipe interface, a wide weld, and a reduced amount of flow in the direction of the weld. Welding had little effect on the mean helical content of polypropylene welds, although an increase in crystallinity at the centerline was shown.

Welding reduced the amount of crystalline phase orientation parallel to the pipe axis. The orientation changed to the flow direction of the weld and the amount of realignment decreased with increasing plate removal time, and the orientation dropped sharply at the centerline.

Transmitted light microscopy did not always show morphological changes, which were revealed by scanning electron microscopy examination of etched samples such as the extent of HAZ, or by Fourier Transform Infrared Spectroscopy such as annealed regions. The mode of etching (acid and solvent) involved the removal of disordered material between the lamellae and at the spherulitic boundaries, and it is probable that the attack was on the beta-spherulites.

Reference: Stevens SM: Structure evaluation of polyethylene and polypropylene hot plate welds. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

35.3.2 Vibration Welding

PP copolymer

A vibration welding design of experiments of a non-PP backed carpet to six PP copolymer substrates has shown that the bonding mechanism was due to to mechanical interlocking between molten PP and the nonwoven backing material. Three major welding parameters (time, pressure, and amplitude) as well as six different substrates were studied. The results indicated that the weld amplitude and weld time were the two most dominant factors in affecting the bond strength, followed by weld pressure. It was found that a weld time of 2 seconds, weld pressure of 0.35 MPa (51 psi) and amplitude of vibration of 1.75 mm (0.069 inches) produced the strongest bond.

Reference: Wu CY, Ayres T: Vibration welding of carpet to polypropylene substrate. *Welding in the World*, 49(7/8), p. 73, July/August 2005.

Washington Penn Plastic: PPC5UF0
(form: 3.2 mm (0.126 inch) thick injection-molded plaques; reinforcement: organoclay)

PP copolymer was compounded with 0, 3, and 6 wt.% organoclay. Plaques of thickness 3.2 mm (0.126 inches) were machined into plates of dimensions 50 × 100 mm (2.0 x 3.9 inches), which were welded at a frequency of 211 Hz and a peak-to-peak amplitude of 1.8 mm (0.071 inches). The weld pressure was varied from 1 to 4 MPa (145–580 psi) and the target melt-down was varied from 1 to 3 mm (0.04-0.12 inches).

Table 35.8. Welding Details and Tensile Results for Hot Plate Welded Isotactic Pipes Made from Polypropylene Copolymerized with Ethylene

Weld	Total Heating Time, s	Plate Temperature °C (°F)	Heating and Welding Pressure, MPa (psi)	Plate Removal Time, s	Tensile Strength, MPa (psi)
Weld 1	200	205 (401)	0.1 (15)	2	20.8 (3020)
Weld 2	200	205 (401)	0.1 (15)	50	20.4 (2960)
Weld 3	200	205 (401)	0.1 (15)	70	10.7 (1550)
Parent Material					22.0 (3190)

Results showed that the addition of organoclay material to PP matrices causes large drops in weld strength. The weld tensile strength was observed to decrease approximately 25% for each 3% of organoclay added. This is believed to be caused by alignment of the clay platelets at the weld. Relative to this organoclay level effect, the effects of welding conditions on weld strength is small. Fourfold increases in melt pressure caused a 10% increase in weld strength. No significant effect of melt-down was observed.

Reference: Bates P J, Braybrook C, Kisway T, Tucker B, Gopakumar TG, Pagé DJYS, Wu CY: Vibration welding polypropylene-based nanocomposites. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

Huntsman: **AP 6120-HS** (form: injection-molded plaques)

This work compares the differences in weld quality between orbital and linear vibration welding of various thermoplastics. The control parameters were varied as follows:

- Amplitude: 0.76–1.8 mm (0.03-0.07 inches) peak-to-peak
- Clamping pressure: 1.0–6.9 MPa (145–1000 psi)
- Collapse: 0.76–1.8 mm (0.03-0.07 inches)

Results showed that there was little difference in the maximum weld strength between linear and orbital welding. Therefore, orbital welding enables a 30% or more reduction in cycle time without loss in maximum weld strength.

For a given clamping force setting, with orbital motion it was possible to weld with a 10% lower vibration amplitude and achieve the same weld strength as with a linear motion. The advantage of lower minimum vibration amplitude for welding is the ability to weld higher unsupported walls and the ability to design more massive tooling for larger parts without overloading the welding machine.

Reference: Grewell DA, Benatar A: An application comparison of orbital and linear vibration welding of thermoplastics. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

Hoechst AG: Hostalen

The vibration weld was featureless, and there was a sharp transition between the weld and the parent. DSC results showed that the crystalline structure of the parent polymer had been affected by the welding conditions, and the main effect was the disappearance of the beta-crystalline form within the weld.

The welds had inferior mechanical properties to those of the sheet from which the samples were taken. The impact strengths of the weld were 11% of the parent material strength. It is possible that the low impact strengths could be due, in part, to the abrupt changes in visible microstructure between the weld and parent.

Reference: Stevens SM: The effect of welding on the α- and β- crystalline forms of polypropylene. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

35.3.3 Extrusion Welding

Vestolen P9422, Vestolen P9522 (features: extruded 10 mm (0.39 inch) thick sheet)

The granulate for the weld seam extrusions and the sheet materials were taken from the same production lots. The extrusion welding processing window is given in Table 35.9.

Reference: Jaussent V, Ehrenstein GW: Extrusion welds of different types of polypropylene. *Schweissen und Schneiden,* 50(10), p. 656, October 1998.

Table 35.9 Processing Window for Extrusion Welding of Polypropylene Copolymers

Polypropylene Grade	Extrusion Material	Welding Speed, mm/s	Hot Gas Temperature, °C (°F)	
			Minimum	Maximum
Vestolen P9422	Random copolymer	4	280 (536)	320 (608)
		8	290 (554)	350 (662)
Vestolen P9522	Block copolymer	4	280 (536)	350 (662)
		8	300 (572)	360 (680)

35.3.4 Laser Welding

Basell Polyolefins: PP copolymer (form: 3.2 mm (0.126 inch) thick injection-molded plaques)

In order to understand the weldability of different-colored TPO to PP using laser welding, a three-factor (laser power, welding time, and scanning speed) two-level full factorial design of experiments was performed. Natural PP copolymer was used as the transparent layer. Three TPO materials (black, blue, and tan) from Basell Polyolefins, consisting of PP, talc filler, and rubber modifiers, were used as the absorbing layer. The samples were welded using a 200 W flash-lamp-pumped Nd:YAG laser with a wavelength of 1.06 μm.

It was found that the 3.2 mm (0.126 inch) thick natural PP had a transmission rate of 29%. It was also found that the black TPO had the most laser absorption, followed by the blue, and then the tan. Therefore, the black TPO required the least amount of welding time to reach the maximum joint strength. In addition, as the scanning speed was reduced, the time required to reach maximum joint strength was also reduced.

Reference: Wu CY, Cherdron M, Douglas DM: Laser welding of polypropylene to thermoplastic polyolefins. ANTEC 2003, Conference proceedings, Society of Plastics Engineers, Nashville, May 2003.

35.3.5 Induction Welding

Basell Polyolefins: Pro-fax 7523

A commercial high-frequency generator (Emabond Systems HD500) was used for making the induction welds. Pressure applied by an air cylinder was used to control the weld interface pressure; two weld pressures of 0.21 MPa (30 psi) and 0.41 MPa (60 psi) were used.

Relative weld strengths as high as 55% were demonstrated, although it should be remembered that while this study focused on the tensile strengths of welds, in induction welding the weld joints are mainly subjected to shear stresses.

Reference: Stokes VK: Experiments on the induction welding of thermoplastics. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

36 Polyurethane

36.1 Ultrasonic Welding

Dow Chemical: Dow XU72523.01 (features: high heat grade, transparent); **Isoplast 101** (features: impact modified); **Isoplast 301** (features: transparent, low impact)

This study was designed to identify which resins could be effectively ultrasonically welded to themselves and other resins, and to identify the maximum bond integrity. Besides looking at the weld strength of various thermoplastic resins, this study explores the effects of gamma radiation and ethylene oxide (EtO) sterilization on the strength of these welds. A wide variety of resins used in the healthcare industry were evaluated including rigid thermoplastic polyurethanes (RTPUs).

The strength of customized "I" beam test pieces was tested in the tensile mode to determine the original strength of each resin in the solid, nonbonded test piece configuration. Data from this base-line testing was used to determine the percent of original strength that was maintained after welding. The most commonly used energy director for amorphous resins, a 90° butt joint, was used as the welding architecture.

Every attempt was made to make this a "real world" study. The aim during the welding process was to create a strong weld while maintaining the aesthetics of the part. One of the most important factors in determining whether or not a good weld had been achieved was the amount of flash, or overrun noticed along both sides of the joint. Another characteristic of a good weld was a complete wetting of the cross-sectional weld area.

Overall, it appeared that resin compatibility and the ability to transfer vibrational energy through a part, and not similar glass transition temperatures, were the overriding characteristics that led to the best welds. Although not shown in this study, it should be noted that the ability of a resin to be welded is also a function of the architecture of the ultrasonic weld. Some resins that welded well in the architecture used for this study may not weld well with other architectures.

As a group, the RTPUs did not ultrasonically bond well with the polystyrenes or the polycarbonates. The high heat RTPU did not bond very well with any of the resins in the study, although some degree of bonding was achieved with every resin. The impact modified and clear RTPUs bonded very well with the ABS resins, and to a lesser degree with the RTPUs and SAN resins. Sterilization by both EtO and gamma did not significantly affect the bonds in this short-term study.

Reference: Kingsbury RT: Ultrasonic weldability of a broad range of medical plastics. ANTEC 1991, Conference proceedings, Society of Plastics Engineers, Montreal, May 1991.

36.2 Solvent Welding

Dow Chemical: Isoplast 301 (features: transparent)

In tests conducted to evaluate the solvent bondability/compatibility of plasticized PVC tubing to rigid, transparent thermoplastics, no evidence of post-assembly crazing could be found with luers made of RTPU. The ease of insertion was superb in every case, except when acetone was the solvent. Satisfactory bonds could only be obtained with THF, which gave a very strong bond, and with certain specific blends of MEK or methylene chloride in cyclohexanone—particularly those mixtures with 30–50% MEK. Besides THF, a preferred solvent blend that provides maximum bond integrity is a 30:70 cocktail of MEK in cyclohexanone.

Reference: Haskell A: Bondability/compatibility of plasticized PVC to rigid, transparent thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

37 Styrenics

37.1 Polystyrene

37.1.1 Heated Tool Welding

PS (form: foam)

It was impossible to achieve a welding factor greater than 0.8 for hot plate welding of PS foam.

Reference: Potente H, Wilke L: Welding thermoplastic foams. ANTEC 2005, Conference proceedings, Society of Plastics Engineers, Boston, May 2005.

37.1.2 Ultrasonic Welding

PS (note: with regrind polystyrene)

The effect of the regrind polystyrene on the strength of the ultrasonically welded joint follows the same trend as that observed in the mechanical properties. The shear strength of the virgin polystyrene is 30.2 MPa (4380 psi), which decreases to 21.3 MPa (3090 psi) for the 100% regrind samples. Comparing the 29% reduction of the shear joint strength to the 27% reduction of the tensile strength (because of the increase of regrind from 0% to 100%), it could be concluded that the effect of regrind polystyrene on the ultrasonic welding process is mainly due to the change of mechanical properties of the polymer. In testing, the addition of regrind polystyrene does not significantly affect the ultrasonic welding process.

In this investigation, the data show that the greatest decrease in both tensile and shear strength occurs when the amount of the regrind polystyrene exceeds 25%. Therefore, some recommendations for the production process may be based on this data.

Other experiments have indicated that the variation of the amount of the regrind polystyrene has only a slight change on the viscosity of the polymers. This may be considered as one of the reasons that the regrind polystyrene does not significantly alter the ultrasonic welding process.

As to the reduction of the strength of the regrind polystyrene, it is most likely because the regrinding process introduces some unavoidable contamination, and also creates a change as the polymer chains are shortened.

Reference: Infantino B: Ultrasonic welding of regrind plastics. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

BASF AG: Polystyrol

Welding preference is given to ultrasonic techniques.

Reference: *Polystyrol Product Line, Properties, Processing*, Supplier design guide (B 564 e/2.93), BASF Aktiengesellschaft, 1993.

Dow Chemical: Styron 666D (features: moderate molecular weight); **Styron 685** (features: high molecular weight)

This study was designed to identify which resins could be effectively welded to themselves and other resins, and to identify the maximum bond integrity. Besides looking at the weld strength of various thermoplastic resins, this study explores the effects of gamma radiation and ethylene oxide (EtO) sterilization on the strength of these welds. A wide variety of resins used in the healthcare industry were evaluated, including general purpose polystyrene (GPPS).

The strength of customized “I” beam test pieces was tested in the tensile mode to determine the original strength of each resin in the solid, nonbonded test piece configuration. Data from this base-line testing was used to determine the percent of original strength that was maintained after welding. The most commonly used energy director for amorphous resins, a 90º butt joint, was used as the welding architecture.

Every attempt was made to make this a “real world” study. The aim during the welding process was to create a strong weld while maintaining the aesthetics of the part. One of the most important factors in determining whether or not a good weld had been achieved was the amount of flash or overrun noticed along both sides of the joint. Another characteristic of a good weld was a complete wetting of the cross-sectional weld area. The problem here, however, was that only clear polymers used as the top piece allowed the whole weld to be seen.

Almost all resins involved in the study could be welded together with some degree of success. Overall, it appeared that resin compatibility and the ability to transfer vibrational energy through a part, and not similar glass transition temperatures, were the overriding characteristics that led to the best welds. Although not shown in this study, it should be noted that the ability of a resin to be welded is also a function of the architecture of the ultrasonic weld. Some resins that welded well in the architecture used for this study may not weld well with other architectures.

The GPPSs were very brittle and notch sensitive. This led, in numerous instances, to premature failure during testing because of the naturally occurring flaws in the joint area. This in turn led to a very high standard deviation in most cases. Because of the brittle nature of these resins versus the design used in the test pieces, it was not possible to make any definite conclusions on the bond strength. It is reasonable to expect that any weld architecture involving GPPS will have similar weld area flaws, and thus it is appropriate to conclude that the bond strength of GPPS ultrasonic welds will likely experience a high degree of variability, which should be compensated for during part design.

Reference: Kingsbury RT: Ultrasonic weldability of a broad range of medical plastics. ANTEC 1991, Conference proceedings, Society of Plastics Engineers, Montreal, May 1991.

Dow Chemical: Styron

Excellent results are obtained by using ultrasonic welding to bond Styron to itself.

Reference: *General Purpose Styron*, Supplier design guide (301-678-1085), Dow Chemical Company, 1985.

37.1.3 Vibration Welding

PS (form: foam)

During vibration welding of PS foam, the pores become distorted in the direction of flow, and thus lead to a reduction in weld seam strength in the same way as for the orientation of glass fibers. The more pores that are deformed in the melting zone, the lower the strength of the joint. It was impossible to achieve a welding factor greater than 0.8.

Reference: Potente H, Wilke L: Welding thermoplastic foams. ANTEC 2005, Conference proceedings, Society of Plastics Engineers, Boston, May 2005.

37.1.4 Spin Welding

PS

The highly brittle standard polystyrene can be friction welded with difficulty. Maximum welding factors (strength of weld/strength of bulk material) of 0.45 were attained with low axial pressure (0.05–1 MPa; 7–145 psi).

Reference: Tappe P, Potente H: New findings in the spin welding of plastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

37.1.5 Laser Welding

PS

In these experiments, welds were made between 0.4 mm (0.016 inch) thick clear PS (top) and 1.5 mm (0.059 inch) thick black PS (bottom) using a diode laser with an 828 nm wavelength. The pressure was set to 69 kPa (10 psi). The power was varied from 50 to 1000 mW, the travel speed was varied between 30 and 140 mm/s (1.2–5.5 inches/s) and the focal spot size was varied between 25 and 50 μm (0.001–0.002 inches).

Results showed that the weld width was directly proportional to heat input and power level. For the 25 μm (0.001 inch) focal spot lens, the minimum weld width was approximately 55 μm (0.0022 inches). With heat input lower than 0.0025 J/mm, a relatively uniform weld width of 17 μm (0.0007 inches) was produced. Welds separated by as little as 25–35 μm (0.0010–0.0014 inches) could be generated.

Reference: Grewell D, Jerew T, Benatar A: Diode laser microwelding of polycarbonate and polystyrene. ANTEC 2002, Conference proceedings, Society of Plastics Engineers, San Francisco, May 2002.

37.1.6 Solvent Welding

BASF AG: Polystyrol

Polystyrene parts can be bonded together with the aid of solvents such as toluene or methylene chloride, but only to parts made of the same material.

Reference: *Processing of Polystyrol*, Supplier design guide, BASF Aktiengesellschaft, 2007.

Dow Chemical: Styron 615APR (features: transparent)

In tests conducted to evaluate the bondability/compatibility of plasticized PVC tubing to rigid, transparent thermoplastics, none of the solvent combinations with polystyrene came close to meeting the accepted criteria for bond strength. Assembly was easy except with acetone, where the tubing was difficult to insert and the luers were immediately cracked upon contact with the acetone. Straight methylene chloride and straight methyl ethyl ketone (MEK) produced slight crazing.

The solvents that worked best with polystyrene were either straight cyclohexanone or 1,2-dichloroethane.

Reference: Haskell A: Bondability/compatibility of plasticized PVC to rigid, transparent thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

Dow Chemical: Styron

Parts molded from Styron GPPS can be solvent welded to each other using any of a number of effective solvents. Care should be given to safety considerations according to the properties of the solvent.

Reference: *General Purpose Styron*, Supplier design guide (301-678-1085), Dow Chemical Company, 1985.

37.1.7 Adhesive Bonding

PS Huntsman: XC2245-HIY-9100

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl

Table 37.1. Shear Strengths of Huntsman XC 2245-HIY Polystyrene to Polystyrene Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[b]

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive General Purpose)	**Depend 330** (Two-Part No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	4 rms	450 (3.1)	1350 (9.3)	>1750[a] (>12.1)[a]	500 (3.5)	350 (2.4)	1350 (9.3)
Roughened	32 rms	750 (5.2)	>800[a] (>5.5)[a]	750 (5.2)	800 (5.5)	350 (2.4)	1350 (9.3)
Antioxidant	0.06% Irganox 245 0.02% Irganox 1076	450 (3.1)	>1450[a] (>10.0)[a]	>3300[a] (>22.8)[a]	1250 (8.6)	350 (2.4)	1350 (9.3)
UV stabilizer	0.31% Tinuvin 328 0.31% Tinuvin 770	450 (3.1)	1350 (9.3)	>1750[a] (>12.1)[a]	500 (3.5)	350 (2.4)	500 (3.5)
Impact modifier	15% Kraton D1101	900 (6.2)	>2100[a] (>14.5)[a]	>1750[a] (>12.1)[a]	>2300[a] (>15.9)[a]	150 (1.0)	>2000[a] (>13.8)[a]
Flame retardant	4% Saytex HBCD-SF 1% Antimony Oxide	450 (3.1)	750 (5.2)	>1750[a] (>12.1)[a]	>850[a] (>5.9)[a]	50 (0.3)	1350 (9.3)
Lubricant	0.5% Zinc Stearate	450 (3.1)	>1200[a] (>8.3)[a]	>1750[a] (>12.1)[a]	500 (3.5)	50 (0.3)	1350 (9.3)
Colorant	4% CP204230	450 (3.1)	450 (3.1)	1500 (10.3)	500 (3.5)	350 (2.4)	1000 (6.9)

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches/second (0.25 mm/s).

While the bond strengths in Table 37.1 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 37.1, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in “real world” applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 instant adhesive, when used in conjunction with Prism Primer 770, and Flashcure 4305 light cure adhesive achieved the highest bond strengths on PS, typically substrate failure. Prism 401 instant adhesive, Loctite 3105, a light curing acrylic adhesive, Loctite 3030 adhesive and Hysol 3631 hot melt adhesive achieved the second highest bond strengths. Loctite 3651 and Hysol 7804 hot melt adhesives achieved the lowest bond strengths. The addition of an impact modifier additive increased the bondability of PS with cyanoacrylate and light curing acrylic adhesives.

Surface Treatments: The use of Prism Primer 770, when used in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused a statistically significant increase in the bondability of all the formulations of PS evaluated, except for the roughened PS, where Prism Primer 770 or 7701 caused a statistically significant decrease in its bondability. Surface roughening caused a statistically significant increase in the bond strengths achieved on unprimed PS when using cyanoacrylate adhesives, but had no statistically significant effect when using acrylic adhesives.

Other Information: Polystyrene is compatible with acrylic adhesives, but can be attacked by their activators before the adhesive has cured. Any excess activator should be removed from the surface immediately. Polystyrene is incompatible with anaerobic adhesives. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

Dow Chemical: Styron

Many of the common, rubber-based adhesives may be used to bond parts made of Styron resin to a variety of other materials such as metal, wood, and glass. Choose the adhesive carefully to prevent premature failure of the composite due to stress cracking.

Reference: *General Purpose Styron*, Supplier design guide (301-678-1085), Dow Chemical Company, 1985.

37.1.8 Mechanical Fastening

Dow Plastics: Questra

Parts molded of Questra crystalline polymers require more attention to snap-fit design than some other polymers. In general, due to the low elongation associated with glass-reinforced polymers, longer lever arms need to be designed into snap features. Because the material is stiffer than unfilled thermoplastics, the amount of engagement may also be reduced, which will reduce the amount of flex the feature will see, thereby lowering the stresses on the part.

Reference: *Questra Design Guide*, Supplier design guide, Dow Plastics, 1999.

37.2 Impact Polystyrene

37.2.1 Heated Tool Welding

IPS

For impact polystyrene (IPS), hot plate welds of the same strength as the parent material were readily achieved. However, the amount of material displaced was large. An essential requirement for the control of material displacement was the use of displacement limit stops. The position of the stops was important, since improved joint strength was achieved for stops set at 1.0 mm (0.039 inches), which was the maximum stop position on the equipment used. The weld consolidation period could be limited to <5 seconds as an aid to process efficiency, as both pressure and time had little effect on tensile strength.

It is apparent that sufficient heat-soaked material, behind the melt fronts, must be available to provide >2.5 mm (0.1 inches) material displacement in the consolidation stage. At a hot plate temperature of 205°C (401°F), a minimum of 20 seconds heating time was necessary to provide the required heat-soaked material. However, using a hot plate temperature of up to 255°C (491°F), a reduced heating time, <15 seconds, would fulfill the requirements of >2.5 mm (0.1 inches) displacement in the consolidation state to give joints with high tensile strength values.

Reference: Watson M, Murch M: Recent developments in hot plate welding of thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

37.2.2 Ultrasonic Welding

IPS

In ultrasound butt welding in impact-resistant polystyrene with V-shaped edge preparation, the ultimate strength of the joints is maximum after complete melting of the concentrator (V-shaped projection) and subsequent deformation of the welding zone by 0.05–0.10 mm (0.002–0.004 inches). Edge preparation increases the strength of the welded joint, improves its external appearance, and shortens the welding time. The optimum height of the V-shaped projection is 0.3–1.0 mm (0.012–0.039 inches).

Reference: Volkov SS: Effect of dimensions of the gap between the edges on the strength of ultrasound welded joints in rigid plastics. *Welding International*, 17(6), p. 482, 2003.

Dow Chemical: Styron 498 (features: high impact)

This study was designed to identify which resins could be effectively ultrasonically welded to themselves and other resins, and to identify the maximum bond integrity. Besides looking at the weld strength of various thermoplastic resins, this study explores the effects of gamma radiation and EtO sterilization on the strength of these welds. A wide variety of resins used in the healthcare industry were evaluated including high impact polystyrene (HIPS).

The strength of customized “I” beam test pieces was tested in the tensile mode to determine the original strength of each resin in the solid, nonbonded test piece configuration. Data from this base-line testing was used to determine the percent of original strength that was maintained after welding. The most commonly used energy director for amorphous resins, a 90° butt joint, was used as the welding architecture.

Every attempt was made to make this a “real world” study. The aim during the welding process was to create a strong weld while maintaining the aesthetics of the part. One of the most important factors in determining whether or not a good weld had been achieved was the amount of flash or overrun noticed along both sides of the joint. Another characteristic of a good weld was a complete wetting of the cross sectional weld area. The problem here, however, was that only clear polymers used as the top piece, allowed the whole weld to be seen.

Almost all resins involved in the study could be welded together with some degree of success. Overall, it appeared that resin compatibility and the ability to transfer vibrational energy through a part and not similar glass transition temperatures, were the overriding characteristics that led to the best welds. Although not shown in this study, it should be noted that the ability of a resin to be welded is also a function of the architecture of the ultrasonic weld. Some resins that welded well in the architecture used for this study may not weld well with other architectures.

The HIPS resin tested bonded well to itself, the other polystyrenes, and the low acrylonitrile (AN) SAN grade. As with the other polystyrenes in the study, HIPS did not bond well to the urethanes. It showed limited bonding compatibility to the PCs, the higher AN SAN, and the higher heat RTPU. Examination of these welds after testing showed that the HIPS had melted, but the energy director on these higher Tg materials was still intact (not melted) and was embedded in the HIPS. This would indicate that the HIPS resin became the glue that held the pieces together, and there was limited molecular intermeshing. Overall, the HIPS samples were unaffected by the gamma sterilization although the EtO sterilization did reduce the bond strength somewhat for most of the HIPS resin combinations.

Reference: Kingsbury RT: Ultrasonic weldability of a broad range of medical plastics. ANTEC 1991, Conference proceedings, Society of Plastics Engineers, Montreal, May 1991.

IPS

The results from ultrasonic lap welds with IPS show clearly that an optimum welding force exists. The optimum welding force was 200 N (45 lbf) at an amplitude of 29 μm (0.0011 inches). Maximum ultimate breaking forces are only achieved at or near the optimum welding force and cannot be increased any further after an optimum welding time.

The generator energy and thus also the change in damping are not in themselves process parameters that can be used to monitor the weld seam quality. In order to reliably monitor the quality of the weld seam strength during the welding process, it is necessary to control the welding force, the welding time, and the amplitude and/or displacement.

Reference: Netze C, Michaeli W: Correlation of welding parameters, energy conversion and mechanical weld seam properties for ultrasonic welding. ANTEC 1991, Conference proceedings, Society of Plastics Engineers, Montreal, May 1991.

Dow Chemical: Styron XL-8035MFD (applications: floppy disk; features: 45 Rockwell M hardness, 85 Rockwell L hardness)

Ultrasonic welding is performed easily with Styron XL-8035 MFD resin using either 20 kHz or 40 kHz welders. In general, ultrasonic benefits and procedures for Styron XL-8035 MFD (microfloppy disk) resin are similar to those of Styron 498 or XL-8023VC. Welding in the energy or time mode is recommended—the energy mode is preferred. Compared with welding ABS MFD parts, HIPS MFD parts may require slight adjustments based on welder set-up and fixturing. Whether the MFD is made of ABS or HIPS, the same welding cycle and weld strength can be achieved.

Reference: *Styron XL-8035 MFD High Impact Polystyrene Resin for Microfloppy Diskettes*, Supplier marketing literature (301-1607-791X SMG), Dow Chemical Company, 1991.

Chevron: 6800

Far field ultrasonic welding of HIPS was successful. The weld strengths improved with increasing pressure, amplitude of vibration at the joint interface, and weld time. For long weld times, the weld strength decreased slightly with increasing weld time due to increased flow resulting in unfavorable molecular orientation.

Reference: Benatar A, Cheng Z: Far-field ultrasonic welding of thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

Chevron: 6800

Near field ultrasonic welding of IPS was successful, producing stronger bonds than semicrystalline materials. It was generally found that increasing the weld pressure initially increases the weld strength, with further increases in pressure, decreasing the strength due to unfavorable molecular alignment. Increasing the weld time increased energy dissipated and strength. Increasing the amplitude of vibration increased the energy dissipated and strength (although not as much as in semicrystalline materials)—with the exception of low amplitudes.

Reference: Benatar A, Eswaran RV: Near-field ultrasonic welding of thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

Dow Chemical: Styron (manufacturing method: injection molding)

Excellent results are obtained from ultrasonic welding of Styron to itself.

Reference: *Styron Polystyrene Resins for Applications Requiring Impact Resistance*, Supplier design guide (301-471-1281), Dow Chemical Company, 1981.

37.2.3 Solvent Welding

Dow Chemical: 489MW (form: injection-molded ASTM flexural test specimens)

An investigation was conducted to evaluate replacements for methylene chloride in the solvent welding of ABS and impact PS. Fourteen candidate solvents were experimentally considered. These were divided into three general categories: traditional, “green”, and “clean”.

Results indicated that solvent evaporation rate was critical in the development of bond strength. Specifically, solvents with high vapor pressures displayed superior performance in all cases. This suggests that a trade-off must be made between cycle time of the bonding operation and the amount of solvent vapor in the air.

Ethyl acetate, methyl acetate and acetone all surpassed the performance of the methylene chloride baseline.

The low solubility parameters of the green solvents made them unacceptable candidates from a mechanical properties perspective. Additionally, the clean solvent, ethyl lactate, under-performed the other candidates even though its solubility parameter was close to that of methylene chloride.

Finally, N-methyl-2-pyrrolidinone was a poor performer, relative to the methylene chloride baseline; however, if elevated temperature, positive pressure, or vacuum are employed, adequate properties can be obtained from this clean solvent bonding approach.

Reference: Desai J, Barry CMF, Mead JL, Stacer RG: Solvent welding of ABS and HIPS. A case study in methylene chloride substitution. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

Dow Chemical: Styron 6000

Parts molded from Styron 6000 series resins can be solvent bonded together with such solvents as MEK, acetone, ethylene dichloride, perchloroethylene, and trichloroethylene. Up to 15% (by volume) of unmodified polystyrene can be added to these solvents to increase viscosity.

Solvents are applied by dipping, roller coating, brushing, spraying, flow guns, and other means. For better appearance and strength, tongue-and-groove, lap and V-groove joints are preferred over butt joints.

Reference: *Styron 6000 Ignition Resistant Polystyrene Resins*, Supplier Marketing Literature (301-01673-192R SMG), Dow Chemical Company, 1992.

Dow Chemical: Styron (manufacturing method: injection molding)

Molded parts made of Styron resin may be solvent welded to each other with a number of effective solvents. Methylene chloride is commonly used if a fast-drying solvent is desired. MEK or a mixture of 30% methyl methacrylate monomer and 70 % butyl acetate are effective as medium drying solvents.

Reference: *Styron Polystyrene Resins for Applications Requiring Impact Resistance*, Supplier design guide (301-471-1281), Dow Chemical Company, 1981.

37.2.4 Adhesive Bonding

Dow Chemical: Styron (manufacturing method: injection molding)

Many of the common rubber-based adhesives may be used to bond parts made of Styron resin to a variety of other materials such as metal, wood, and glass. Adhesives should be chosen carefully to prevent premature failure of the composite due to stress cracking.

Reference: *Styron Polystyrene Resins for Applications Requiring Impact Resistance*, Supplier design guide (301-471-1281), Dow Chemical Company, 1981.

37.3 Acrylonitrile-Butadiene-Styrene Copolymer

37.3.1 General

BASF AG: Terluran

Terluran moldings and extruded stock can be welded together by hot-shoe, spin, and ultrasonic techniques. Preliminary trials are often essential, because the bond strength and the appearance of the weld depend considerably on the machine parameters, as well as on the adherends.

Reference: *Terluran Product Line, Properties, Processing*, Supplier design guide (B 567e/(8109) 9.90), BASF Aktiengesellschaft, 1990.

37.3.2 Heated Tool Welding

Bayer: Lustran

The recommended hot plate welding parameters for Lustran ABS are:

- Hot plate temperature: 230–410ºC (446–770ºF)
- Joining pressure: 0.4–0.8 N/mm^2 (58–116 psi)

Reference: *Hot Plate Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

GE Plastics: Cycolac GPP 4600

High strengths can be attained in heated tool welds of the window-frame grade of ABS. When the flash is retained, the apparent weld strength can be higher than the strength of the resin. The relative weld strengths with the flash machined off compare very favorably with the relative strengths of 98% that can be attained in vibration welds of this material. Such high strengths can be achieved without drying the material.

This grade of ABS can be welded over a wide weld processing window: hot plate temperatures between 205 and 246ºC (401 and 475ºF) and melt times of 10–20 seconds.

Reference: Stokes VK: The hot-tool and vibration welding of acrylonitrile-butadiene-styrene. *Polymer Engineering and Science*, 37(4), p. 692, April 1997.

GE Plastics: Cycolac GPP4600

This study showed that high strengths can be obtained in hot tool welds of a window frame grade of ABS. The weld strength, when the flash is retained, can be as high as 95% of the strength of the base resin. This relative weld strength compares favorably with the relative strengths of 95% that can be obtained in vibration welds of this material. However, it should be noted that for the same relative strength, vibration welds will actually have higher true strengths because in such welds, the flash does not contribute to the strength as it does in heated tool welding.

Reference: Stokes VK: The hot tool welding of acrylonitrile-butadiene-styrene. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

BASF AG: Terluran 967K

Tests on hot plate welds of ABS after thermal aging in air showed that elevated temperatures reduced elongation and tensile strength of ABS welds more than the parent material; cross-sectional areas in welded specimens were reduced more than 30%; and yellowing occurred. After immersion in warm and boiling water, ABS hot plate welds showed loss of tensile strength (30–70%) and elongation (40–70%), and whitening occurred (Table 37.2).

Losses in unsaturation in the polybutadiene segment of ABS and an increase in carbonyl group concentration occurred, and were more significant in welds than in the parent material. The main target for degradation was the butadiene segment in ABS. Mechanochemical degradation was initiated during welding and accelerated during subsequent ageing. FTIR (Fourier Transform Infrared Spectroscopy) is a potential technique for detecting the extent of degradation in ABS welds.

Table 37.2. The Effect of Thermal Air Aging and Boiling Water on the Properties of Hot Plate Welds of ABS

ABS Sample	Exposure Type	Aging temp.	Aging Time	Ultimate Tensile Strength		Elongation at Break	
		°C(°F)	days	MPa (psi)	% Retained	mm (inches)	% Retained
Hot plate weld	thermal air aging	120 (248)	3	19.7 (2860)	61	0.9 (0.035)	42
Parent	thermal air aging	120 (248)	3	46.1 (6690)	107	2.8 (0.110)	78
Hot plate weld	thermal air aging	120 (248)	7	20.5 (2970)	63	0.9 (0.035)	41
Parent	thermal air aging	120 (248)	7	47.2 (6850)	109	3.1 (0.122)	85
Hot plate weld	thermal air aging	120 (248)	14	12.8 (1860)	40	0.7 (0.028)	33
Parent	thermal air aging	120 (248)	14	39.1 (5670)	91	2.5 (0.098)	67
Hot plate weld	boiling water	100 (212)	3	9.3 (1350)	29	0.6 (0.024)	29
Parent	boiling water	100 (212)	3	41.4 (6000)	96	6.5 (0.256)	181
Hot plate weld	boiling water	100 (212)	7	12.6 (1830)	38	0.7 (0.028)	31
Parent	boiling water	100 (212)	7	40.5 (5870)	94	5.4 (0.213)	150

Reference: Tavakoli SM: The effect of ageing on structure and properties of hot plate welds in acrylonitrile-butadiene-styrene. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

37.3.3 Ultrasonic Welding

Bayer: Lustran ABS

At a frequency of 20 kHz, an amplitude of 20–30 μm is recommended for ultrasonic welding of Lustran ABS.

Reference: *Ultrasonic Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

ABS (form: AWS standard test samples)

Thin metal coating of plastic parts for increased optical reflectivity, improved EMI/RFI shielding, decreased permeability, or for decoration has gained more importance in recent years in automotive, electronics, medical, and toy industries. This coating is often found in the weld area and there are concerns regarding its effect on weldability. Therefore, in this work ultrasonic welding of ABS components with metallic coatings was studied to evaluate their effect on weld strength. Two types of coatings were studied: an aluminum coating (55 nm thick) with hexamethyldisiloxane (HMDSO) as its topcoat (15–20 nm) and a stainless steel coating (45 nm thick). The coated ABS was ultrasonically welded to uncoated ABS at a frequency of 20 kHz. Three factors, weld time, weld pressure, and amplitude of vibration, were varied to find near optimum welding conditions. It was found that the aluminum or stainless steel coating had a very small effect on the ultrasonic weld strength for ABS. The maximum weld strength obtained was 28.5, 28.2, and 26.9 MPa (4130, 4090, and 3900 psi) for uncoated, and for aluminum, and stainless steel coated ABS, respectively.

Although the maximum weld strengths obtained for coated specimens were slightly lower than the uncoated specimens, it was within the range of scatter that was observed. Photographs of weld fracture surfaces also tended to confirm these results since under the right welding conditions, the metal coating squeezes out creating a metal-free weld area for a strong joint.

Reference: Mokhtarzadeh A, Benatar A, Wu CY: Effects of metallization coating on ultrasonic welding of ABS. ANTEC 2006, Conference proceedings, Society of Plastics Engineers, Charlotte, May 2006.

Dow: 324/2447 Black

Injection molded parts were ultrasonically welded at a frequency of 20 kHz. The total weld time was 0.9 seconds, with a weld time of 0.4 seconds and a hold time of 0.5 seconds. Energy directors has a 90º triangular-shaped ridge; one had a 0.305 mm (0.012 inch) ridge and the second had a 0.610 mm (0.024 inch) ridge. Of the welded parts, some had been exposed to water for 24 hours, some for 30 minutes, and some not at all.

Results showed that the welded parts that had the energy director of 0.610 mm (0.024 inch) were stronger that those that had the 0.305 mm (0.012 inch) energy director. The small energy director parts had an average failure load of 119.1 kgf (262.6 lbf), with a standard deviation of 7.5 kgf (16.5 lbf). The large energy director parts had a failure load of 127 kgf (280 lbf) with a standard deviation of 8.0 kgf (17.6 lbf).

In the comparison of the wet and dry parts, the large energy director was used as the standard. The wet parts had a surprisingly low failure load of 92.9 kgf (204.8 lbf) with a standard deviation of 7.1 kgf (15.7 lbf).

Reference: Sager RC: Effects of energy director geometry and contamination on ultrasonic welds. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

ABS

The relationship of ultrasonic weld strength and weld/hold force for the materials was studied. It is seen that weld strength is generally inversely proportional to weld force. High weld force promotes strong molecular alignment and results in weaker welds. At the lower weld forces (<455 N; 102 lbf) this relationship does not hold true due to sample warpage. By varying the force during the weld cycle it was found that both short cycle times and strong welds could be achieved simultaneously. Force profiling results in maximized weld strengths while the weld time was decreased.

When both amplitude and force profiling are used, increased strength and decreased weld time result compared to welds made without any profiling. The increased strength comes from the reduced molecular alignment. The reduced cycle time is a result of using high weld forces to initiate the weld. In summary, a relatively high amplitude and force is used to start the weld quickly, and a relatively low amplitude and force is used to complete the weld with minimal molecular alignment.

Reference: Grewell DA: Amplitude and force profiling: studies in ultrasonic welding of thermoplastics. ANTEC

1996, Conference proceedings, Society of Plastics Engineers, Indianapolis, May 1996.

ABS

There were two configurations identified in which amplitude control can benefit ultrasonic welding of thermoplastic parts. In the first two data sets the amplitude was held constant and the weld failure load is between 2500 and 3000 N (560–670 lbf) with a standard deviation of approximately ±258 N (58 lbf). With the first configuration, the standard deviation can be reduced to ±98 N (22 lbf), by simply reducing the amplitude during the welding cycle and using parameters that are similar to those in industrial applications. If the setup allows the use of longer weld times and more collapse, strong welds can be obtained with lower amplitudes—19 µm, the fourth data set in Fig. 37.1. However, by varying the amplitude from 78 to 19 µm, similar results can be obtained with shorter weld times and less part marking.

It has been shown that varying the amplitude during the ultrasonic weld allows better control of the melting process. By reducing the amplitude during the welding cycle it is possible to: maintain the melt within the bond line; obtain stronger welds compared to welds made with a constant amplitude; decrease part marking; and increase weld consistency.

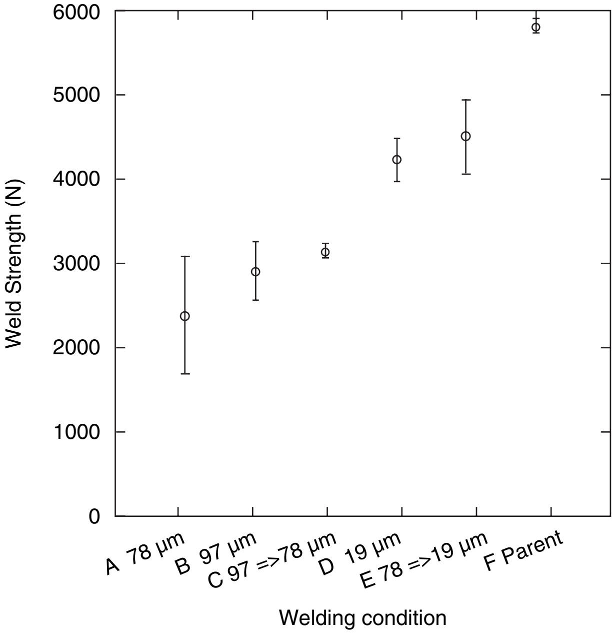


Figure 37.1. Weld strength for ABS test sample ultrasonically welded with various amplitude conditions. Tests with two numbers (i.e., 78 ⇒ 19 µm) represent the use of amplitude profiling.

Reference: Grewell DA, Frantz JL: Amplitude control in ultrasonic welding of thermoplastics. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

Dow Chemical: Magnum 2620 (features: high impact, high gloss); **Magnum 2642** (features: medium impact, low gloss)

This study was designed to identify which resins could be effectively ultrasonically welded to themselves and other resins, and to identify the maximum bond integrity. Besides looking at the weld strength of various thermoplastic resins, this study explores the effects of gamma radiation and EtO sterilization on the strength of these welds. A wide variety of resins used in the healthcare industry were evaluated, including ABS.

The strength of customized "I" beam test pieces was tested in the tensile mode to determine the original strength of each resin in the solid, nonbonded test piece configuration. Data from this base-line testing was used to determine the percent of original strength that was maintained after welding. The most commonly used energy director for amorphous resins, a 90º butt joint, was used as the welding architecture.

Every attempt was made to make this a "real world" study. The aim during the welding process was to create a strong weld, while maintaining the aesthetics of the part. One of the most important factors in determining whether or not a good weld had been achieved was the amount of flash, or overrun noticed along both sides of the joint. Another characteristic of a good weld was a complete wetting of the cross-sectional weld area. The problem here, however, was that only clear polymers used as the top piece, allowed the whole weld to be seen.

Almost all resins involved in the study could be welded together with some degree of success. Overall, it appeared that resin compatibility and the ability to transfer vibrational energy through a part, and not similar glass transition temperatures, were the overriding characteristics that lead to the best welds. Although not shown in this study, it should be noted that the ability of a resin to be welded is also a function of the architecture of the ultrasonic weld. Some resins that welded well in the architecture used for this study may not weld well with other architectures.

The ABS resins incorporated in this study were, overall, the most compatible to ultrasonic welding with dissimilar resins. They ultrasonically bonded well to themselves, SAN, most of the urethanes, and the polycarbonates. However, ABS resins are known to be incompatible with polystyrene and this manifested itself in the form of poor weld strengths. Neither the EtO or gamma sterilization adversely affected the strength of the ABS bonds in this short-term study.

Reference: Kingsbury RT: Ultrasonic weldability of a broad range of medical plastics. ANTEC 1991, Conference proceedings, Society of Plastics Engineers, Montreal, May 1991.

BASF AG: Terluran

Ultrasonic techniques allow bonds to be effected between Terluran and related thermoplastics, that is, Luran (SAN), Luran S (ASA), Vinoflex (PVC) and Lucryl (PMMA).

Reference: *Terluran Product Line, Properties, Processing*, Supplier design guide (B 567e/(8109) 9.90), BASF Aktiengesellschaft, 1990.

GE Plastics: Cycolac

Far field ultrasonic welding of ABS was successful. The weld strengths improved with increasing pressure, amplitude of vibration at the joint interface, and weld time. For long weld times, the weld strength decreased slightly with increasing weld time due to increased flow resulting in unfavorable molecular orientation.

Reference: Benatar A, Cheng Z: Far-field ultrasonic welding of thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

GE Plastics: Cycolac

Near field ultrasonic welding of ABS was successful, producing stronger bonds than semicrystalline materials. It was generally found that increasing the weld pressure initially increases the weld strength, with a further increase in pressure decreasing strength due to unfavorable molecular alignment. Increasing the weld time increased energy dissipated and strength. Increasing the amplitude of vibration increased the energy dissipated and the strength (although not as much as in semicrystalline materials)—with the exception of low amplitudes.

Reference: Benatar A, Eswaran RV: Near-field ultrasonic welding of thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

37.3.4 Vibration Welding

GE Plastics: Cycolac GDT64000 (form: injection-molded plaque)

This study compares the differences in weld quality between orbital and linear vibration welding of various thermoplastics. The control parameters were varied as follows:

- Amplitude: 0.76–1.8 mm (0.030–0.071 inches) peak-to-peak
- Clamping pressure: 1.0–6.9 MPa (145–1000 psi)
- Collapse: 0.76–1.8 mm (0.030–0.071 inches)

Results showed that orbital welding produced welds that had approximately 20% better strength. Also, for a given clamping force setting, with orbital motion it was possible to weld with a 30% lower vibration amplitude and achieve the same weld strength as with a linear motion. The advantage of lower minimum vibration amplitude for welding is the ability to weld higher unsupported walls and the ability to design more massive tooling for larger parts without overloading the welding machine.

Reference: Grewell DA, Benatar A: An application comparison of orbital and linear vibration welding of thermoplastics. ANTEC 1999, Conference proceedings, Society of Plastics Engineers, New York, May 1999.

GE Plastics: ABS

The achievable strengths for vibration welds of ABS to itself and other thermoplastics are given in Table 37.3.

Reference: Stokes VK: Toward a weld-strength data base for vibration welding of thermoplastics. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

37.3.5 Spin Welding

ABS

The maximum weld strengths achieved when welding ABS were 70% of the strength of the base material, whereby the correct combination of speed and axial pressure is essential.

Reference: Tappe P, Potente H: New findings in the spin welding of plastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

37.3.6 Infrared Welding

ABS

This study evaluated the heating characteristics of infrared energy from a quartz-halogen lamp (maximum output at 0.89 μm) on some colored (blue, green, orange, yellow, and red) ABS.

Table 37.3. Achievable Strengths for Vibration Welds of ABS to Itself and Other Thermoplastics

Material Family	**ABS**					
Tensile strength[b], MPa (ksi)	44 (6.4)					
Elongation @ break[b], %	2.2					
Specimen thickness, mm (inches)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	3.2 (0.125)	6.3 (0.25)
Mating Material						
Material family[a]	ABS	M-PPO	PC	PBT	PC/ABS	PEI
Tensile strength[b], MPa (ksi)	44 (6.4)	45.5 (6.6)	68 (9.9)	65 (9.5)	60 (8.7)	119 (17.3)
Elongation @ break[b], %	2.2	2.5	6	3.5	4.5	6
Specimen thickness, mm (in.)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)	3.2 (0.125)	6.3 (0.25)
Process Parameters						
Process type	Vibration welding					
Weld frequency	120 Hz					
Welded Joint Properties						
Weld factor (weld strength/ weaker virgin material strength)	0.9	0.76	0.83	0.8	0.85	0.65
Elongation @ break[b], % (nominal)	2.1	1.45	1.7	1.6	1.8	1.14

[a] ABS: acrylonitrile-butadiene-stryrene copolymer; copolymer; M-PPO: modified polyphenylene oxide; PC: polycarbonate; PBT: polybutylene terephthalate polyester; PC/ABS: polycarbonate/ABS alloy; PEI: polyetherimide.

[b] Strain rate of $10^{-2}s^{-1}$.

Results showed increased transmission as the colors progressed through the spectrum from red to blue. That is, red absorbed more energy relative to the other colors, even though the spectral output was weighted more heavily in the red part of the spectrum. Polymers of different colors can therefore be expected to weld differently by infrared welding. Not only are the issues of pigment-polymer interactions present, such as the differences in weldability caused by white (titanium dioxide), black (carbon black) or other pigments, but heating times and depth of heating are likely to be affected by part color.

Reference: Grimm RA, Yeh H: Infrared welding of thermoplastics. Colored pigments and carbon black levels on transmission of infrared radiation. ANTEC 1998, Conference proceedings, Society of Plastics Engineers, Atlanta, May 1998.

37.3.7 Friction Stir Welding

ABS (form: compression-molded plaque)

Friction stir welding of ABS has been demonstrated to be a viable joining process, with tensile strengths of 96% of the base material strength.

A special tool with a fixed shoe, rather than a rotating shoulder, is necessary to successfully weld thermoplastics. The shoe should have a controllable temperature to optimize the FSW process. Tools with smooth pins are unacceptable. Threaded tools with both straight and tapered pins appear to work well.

The machine spindle speed appears to be the most significant process parameter for FSW of thermoplastics.

Reference: Sorensen CD, Nelson TW, Strand S, Johns C, Christensen J: Joining of thermoplastics with friction stir welding. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

37.3.8 Solvent Welding

Techno Polymer: TFX-450 (form: injection-molded ASTM flexural test specimens)

An investigation was conducted to evaluate replacements for methylene chloride in the solvent welding of ABS and impact PS. Fourteen candidate solvents were experimentally considered. These were divided into three general categories: traditional, “green”, and “clean”.

Results indicated that solvent evaporation rate was critical in the development of bond strength. Specifically, solvents with high vapor pressures displayed superior performance in all cases. This suggests that a trade-off must be made between cycle time of the bonding operation and the amount of solvent vapor in the air.

Acetone outperformed the methylene chloride baseline. Therefore, if appropriate measures can be found to minimize the explosive hazards presented by acetone’s low flash point, this solvent becomes an attractive candidate.

The low solubility parameters of the green solvents made them unacceptable candidates from a mechanical properties perspective. Additionally, the clean solvent, ethyl lactate, under-performed the other candidates even though its solubility parameter was close to that of methylene chloride.

Finally, N-methyl-2-pyrrolidinone was a poor performer relative to the methylene chloride baseline; however, if elevated temperature, positive pressure, or vacuum are employed, adequate properties can be obtained from this clean solvent welding approach.

Reference: Desai J, Barry CMF, Mead JL, Stacer RG: Solvent welding of ABS and HIPS. A case study in methylene chloride substitution. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

ABS (form: pipe)

To investigate concerns over the performance of ABS solvent cements, a study was conducted on solvent cement joint in ABS pipes to determine their mechanical strength and the characteristics of the bond between the pipe and the spigot. Spigots and sockets were joined with Tangit ABS solvent cement (manufactured by Henkel GmbH).

The strength of solvent cement joints depends on the time that is allowed for cure of the joint. Joints cured for 60 days reached a shear strength of 14 MPa (2030 psi). The solvent in the ABS solvent cement dissolved the surfaces of the polymer, giving a profile across the joint where the solvent cement was not detectable.

Reference: Tjandraatmadja GF, Burn LS: A study of the solvent cement bond for PVC and ABS pipe joints. Plastics Pipes XI, Conference proceedings, Munich, Germany, September 2001.

GE Plastics: Cycolac

Cycolac ABS resin can be solvent welded using acetone, methylene chloride or MEK. It can be solvent welded to Noryl PPO using a 4:1 mix of trichloroethylene/MEK.

Reference: *Engineering Themoplastics Design Guide*, Supplier design guide, GE Plastics.

BASF AG: Terluran

Terluran moldings can be very readily bonded together or to Luran S (ASA), Luran 378P and 388S (SAN) articles by means of solvents such as butanone (MEK), acetone, ethyl acetate, dichloroethylene, and cyclohexanone.

Reference: *Terluran Product Line, Properties, Processing*, Supplier design guide (B 567e/(8109) 9.90), BASF Aktiengesellschaft, 1990.

Dow Chemical: Magnum CLR95
(features: transparent)

In tests conducted to evaluate the bondability/compatibility of plasticized PVC tubing to rigid, transparent thermoplastics, transparent ABS (TABS) offered good performance with most bonding solvents. However, straight methylene chloride caused pronounced crazing throughout the luers, as did acetone to a lesser degree. The peak loads for TABS were unsatisfactory or marginal when the solvents were acetone or straight cyclohexanone. It was not too difficult to insert the tubing into the luers made of TABS. Though small amounts of cyclohexanone are often used to improve the ease of assembly, it should be avoided in this case, since cyclohexanone negatively affected bond strengths. The superior solvent for bond strength was 1,2-dichloroethane. MEK is suggested over the 80:20 blend of methylene chloride in cyclohexanone due to the possibility of crazing caused by high amounts of methylene chloride.

Reference: Haskell A: Bondability/compatibility of plasticized PVC to rigid, transparent thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

GE Plastics: Cycolac

Solvents that are effective for bonding ABS are acetone, cyclohexanone, dimethyl formamide, ethylene dichloride, methylene chloride, MEK, tetrahydrofuran, toluene.

Solvents that do not dissolve ABS are ethyl acetate, methyl methacrylate, xylene.

Reference: *Techniques: Adhesive Bonding, Solvent Bonding, and Joint Design*, Supplier technical report (#SR-401A), Borg-Warner Chemicals, Inc., 1986.

37.3.9 Adhesive Bonding

ABS

A study was performed on the effect of vacuum plasma pretreatment with respect to adhesive bond strength on ABS. Two types of high strength epoxy adhesives were used: Eccobond® 2332 (a single-component adhesive) and Eccobond® 45W1 (a two-component adhesive). Eccobond® 2332 was cured for 1 hour at 120°C (248°F), Eccobond® 45W1 was used in a 1:1 ratio with Catalyst 15 and was cured for 24 hours at room temperature. The plasma-treated samples were glued together within one day of the plasma treatment.

Results showed that the bond strength of plasma pretreated samples was three times the value of non-plasma treated samples.

Reference: Lippens P: Vacuum plasma pre-treatment enhances adhesive bonding of plastics in an environmentally friendly and cost effective way. Joining Plastics 2006, Conference proceedings, London, UK, April 2006.

GE Plastics: Cycolac GPM 6300

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches/second (0.25 mm/s).

While the bond strengths in Table 37.4 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 37.4, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 and Super Bonder 414 instant adhesives, Flashcure 4305, and Loctite 3105, a light curing acrylic adhesive, created bonds that were stronger than the ABS substrate. The bond strengths achieved by H3000 and H4500 Speedbonder structural adhesives, 3030 adhesive, Hysol E-90FL and E-20HP epoxy adhesives and Hysol 3631 hot melt adhesive did not achieve substrate failure, but performed exceptionally well. However, the addition of an antistatic agent resulted in a large, statistically significant increase in the bond strengths achieved on ABS. Hysol 1942 and 7802 hot melt adhesives consistently achieved the lowest bond strengths.

Table 37.4. Shear Strengths of Cycolac GPM 6300 ABS to ABS Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[c]

Material Composition		**Loctite Adhesive**					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	3 rms	950 (6.6)	>3500[a] (>24.1)[a]	>3350[b] (>23.1)[b]	>3500[a] (>24.1)[a]	300 (2.1)	>3500[b] (>24.1)[b]
Roughened	48 rms	1400 (9.7)	>3500[a] (>24.1)[a]	>3350[b] (>23.1)[b]	>3500[a] (>24.1)[a]	1300 (9.0)	>3500[b] (>24.1)[b]
Antioxidant	0.1% Irgaphos 168 0.16% Irganox 245 0.04% Irganox 1076	950 (6.6)	>3500[a] (>24.1)[a]	>3350[b] (>23.1)[b]	>3500[a] (>24.1)[a]	150 (1.0)	>3500[b] (>24.1)[b]
UV stabilizer	0.4% UV5411 0.4% UV3346 0.1% Irganox 1076	950 (6.6)	>3500[a] (>24.1)[a]	>3350[b] (>23.1)[b]	>3500[a] (>24.1)[a]	300 (2.1)	>3500[b] (>24.1)[b]
Flame retardant	13.5% DE83R 3% Chlorez 700 S 4% 772VHT Antimony Oxide	950 (6.6)	>3500[a] (>24.1)[a]	>3350[b] (>23.1)[b]	>3500[a] (>24.1)[a]	300 (2.1)	>3500[b] (>24.1)[b]
Smoke suppressant	5% Firebrake ZB zinc borate	650 (4.5)	>3500[a] (>24.1)[a]	>3350[b] (>23.1)[b]	>3500[a] (>24.1)[a]	300 (2.1)	>3500[b] (>24.1)[b]
Lubricant	0.2% N,N'-Ethylene bisstearamide	950 (6.6)	>3500[a] (>24.1)[a]	>3350[b] (>23.1)[b]	>3500[a] (>24.1)[a]	300 (2.1)	>3500[b] (>24.1)[b]
Glass filler	20% Type 3450 glass fiber	950 (6.6)	>3500[a] (>24.1)[a]	>3350[b] (>23.1)[b]	>3500[a] (>24.1)[a]	300 (2.1)	>3500[b] (>24.1)[b]
Colorant	4% 7526 colorant	950 (6.6)	>3500[a] (>24.1)[a]	>3350[b] (>23.1)[b]	>3500[a] (>24.1)[a]	300 (2.1)	>3500[b] (>24.1)[b]
Antistatic	3% Armostat 550	>3500[a] (>24.1)[a]	>3500[a] (>24.1)[a]	>3350[b] (>23.1)[b]	>3500[a] (>24.1)[a]	300 (2.1)	>3500[b] (>24.1)[b]

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] Due to the severe deformation of the block shear specimens, testing was stopped before the acutal bond strength achieved by the adhesive could be determined (the adhesive bond never failed).

[c] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

Surface Treatments: Surface roughening caused a statistically significant increase in the bond strengths achieved when using Black Max 380 instant adhesive and Depend 330 adhesive. The effect of surface roughening could not be determined for Prism 401, Prism 4011, Super bonder 414 instant adhesives, and Loctite 3105 and 3311 light cure adhesives because the bonds created by these adhesives were stronger than the ABS substrate for both the treated and untreated ABS. Likewise, the effect of using Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, could not be determined.

Other Information: ABS can be stress cracked by uncured cyanoacrylate adhesives, so any excess adhesive should be removed from the surface immediately. ABS is compatible with acrylic adhesives, but can be attacked by their activators before the adhesive has cured. Any excess activator should be removed from the surface immediately. ABS is incompatible with anaerobic adhesives. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

ABS

ABS can be bonded as received, using anaerobic, cyanoacrylate, UV, epoxy, and structural acrylic adhesives.

Reference: *The Engineers Guide to Adhesives,* Supplier design guide, Permabond Engineering Adhesives.

GE Plastics: Cycolac

The compatibility of generic adhesive groups with ABS is given in Table 37.5.

Reference: *Techniques: Adhesive Bonding, Solvent Bonding, and Joint Design*, Supplier Technical Report (#SR-401A), Borg-Warner Chemicals, Inc., 1986.

37.3.10 Mechanical Fastening

Bayer: Lustran 448

Tapping and Self-tapping Screws: Table 37.6 lists some average pull-out forces and various torque data for thread-cutting screws tested in Lustran ABS resin. For this data, the screws were installed in the manufacturer's suggested hole diameters. The screw boss outer diameter was approximately twice the screw outer diameter.

Reference: *Engineering Polymers. Joining Techniques. A Design Guide*, Supplier design guide (5241 (7.5M) 3/01), Bayer Corporation, 2001.

GE Plastics: Cycolac

Snap-fit Assemblies: The typical design limit for Cycolac resin in simple tension applications is 0.75% strain. However, in snap-fit joints a general guideline for allowable strain during the interference phase of assembly would be 5%. There are some qualifications required of snap-fit joints using strain levels which are this high. First, the joint must be designed so that once it is assembled it is essentially unstrained. Second, snap-fit joints using high strain levels should not be subjected to multiple assembly and disassembly cycles. The cumulative effects of repeated assembly will result in the eventual failure of highly strained snap-fit joints. Finally, it should be noted that the 5% strain level is only a general guideline and that a number of geometric factors can influence the actual strain level which will be acceptable in any given snap-fit joint. For this reason testing of prototype parts is strongly suggested to verify that a particular snap-fit joint design will provide acceptable performance.

Tapping and Self-tapping Screws: Thread-cutting screws are most frequently recommended for use in non-foamed grades, particularly where the applied load is small and the vibration is minimal. This type of screw cuts threads and is slotted to provide a channel for disposal of chips. The depth of the hole should be slightly deeper than the length of the screw to provide a depository for these chips.

Thread-forming screws, recommended for foamed grades, are better for repeated assembly and can be

Table 37.5. Compatibility of Generic Adhesive Groups with ABS

Characteristic Evaluated	Material Evaluated	Compatibility Ratings for Generic Adhesive Groups[a]				
		Acrylics	Urethanes	Cyanoacrylates[b]	Epoxies	Silicones
Strength	Cycolac ABS	1	4	1	3	5
Impact resistance	Cycolac ABS	2	1	5	4	4
Gap filling	Cycolac ABS	2	1	5	3	1
Cure time	Cycolac ABS	2	5	1	3	3
Ease of application	Cycolac ABS	3	4	1	3	2

[a] Compatibility rating guide: 1: excellent; 2: very good; 3: good; 4: fair; 5: poor. These ratings are generalizations and will differ for specific brands. Chemical compatibility should be evaluated prior to adhesive selection to prevent stress cracking.

[b] Stress cracking is a concern with cyanoacrylates. Careful evaluation of chemical compatibility with the substrate is recommended.

Table 37.6. Thread-cutting Screw Data for Lustran 448 ABS Resin

Screw Size & Type	Screw Length, in. (mm)	Hole Diameter, in. (mm)	Drive Torque, lb in. (Nm)	Recommended Tightening Torque, lb in. (Nm)	Stripping Torque, lb in. (Nm)	Screw Pull-Out, lb (N)
#6, Type 23	0.375 (9.5)	0.120 (3.0)	2.4 (0.28)	4.7 (0.53)	9.1 (1.02)	210 (936)
#6, Type 25	0.500 (12.7)	0.120 (3.0)	2.0 (0.23)	5.6 (0.63)	12.7 (1.44)	193 (856)
#6, Hi-Lo	0.750 (19.0)	0.115 (2.9)	3.0 (0.34)	8.3 (0.94)	19.0 (2.14)	216 (961)
#8, Type 23	0.500 (12.7)	0.136 (3.5)	4.0 (0.45)	6.7 (0.75)	12.0 (1.36)	363 (1616)
#8, Type 25	0.562 (14.3)	0.146 (3.7)	3.8 (0.43)	10.3 (1.16)	23.2 (2.62)	487 (2168)

replaced with little sacrifice in the loss of thread form or holding force. Because these screws force the material to conform to the screw thread and can result in the development of highly stressed areas, caution should be exercised in the use of this screw type in nonfoamed plastic parts.

Hole diameters should be equal to the pitch diameter of thread-cutting screws and 80% of the pitch diameter of thread-forming screws. Minimum depth of screw engagement should be equal to twice the major diameter for the screw. Significant increases in pull-out strength can be realized with slight increases in penetration depths, but only minimal increases will result from increasing the screw diameter at a constant penetration depth.

The use of bosses is preferred for receiving self-tapping screws in many applications. These fasteners can create a notched effect in the component, and the material volume surrounding the tapped hole must be sufficient to absorb the strain of threading. It is suggested that the boss diameter be equal to two to three times the diameter of the hole, and the height should be more than twice the boss diameter. It should be noted that the thickness of the boss at its base may produce an unsightly sink mark on the face surface of the part.

Depending on the application requirements, the use of boss caps may be advantageous. Boss caps are cap-shaped metal fasteners designed to be press-fit onto plastic bosses. These provide reinforcement to prevent the boss from splitting and to permit higher torquing stresses when threaded fasteners are used. A snug fit of the cap on the plastic boss is required.

Reference: *Cycolac ABS Resin Design Guide*, Supplier design guide (CYC-350 (5/90) RTB), General Electric Plastics, 1990.

37.4 Acrylonitrile-Styrene-Acrylate Copolymer

37.4.1 General

BASF AG: Luran S (features: natural resin)

Luran S extruded stock and moldings can be welded by hot shoe or spin techniques. In certain cases, high frequency and ultrasonic welding may be resorted to. Luran S articles may also be welded by ultrasonic techniques to other thermoplastics, for example, SAN, ABS, PVC, and PMMA.

Reference: *Luran S Acrylonitrile Styrene Acrylate Product Line, Properties, Processing*, Supplier design guide (B 566 e/10.83), BASF Aktiengesellschaft, 1983.

37.4.2 Heated Tool Welding

Bayer: Centrex

The recommended hot plate welding parameters for Centrex ASA are:

- Hot plate temperature: 230–410ºC (446–770ºF)
- Joining pressure: 0.4–0.8 N/mm^2 (58–116 psi)

Reference: *Hot Plate Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

37.4.3 Ultrasonic Welding

Bayer: Centrex

At a frequency of 20 kHz, an amplitude of 20–35 μm is recommended for ultrasonic welding of Centrex ASA.

Reference: *Ultrasonic Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

37.4.4 Vibration Welding

GE Plastics: ASA

The achievable strength of vibration welds of acrylonitrile-styrene-acrylate copolymer to itself is given in Table 37.7.

Reference: Stokes VK: Toward a weld-strength data base for vibration welding of thermoplastics. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

37.4.5 Laser Welding

BASF: Ultraform

Suitable Luran S combinations for laser welding are given in Table 37.8.

Reference: *Transmission Laser-Welding of Thermoplastics*, Technical Information (WIS 0003 e 01.2001), BASF Aktiengesellschaft, 2001.

37.4.6 Solvent Welding

Mitsubishi Rayon: Shinko-Lac

Bonding products made of Shinko-Lac ASA can be easily performed using organic solvents. MEK, ethylene dichloride or methylene dichloride are recommended. Solutions of Shinko-Lac ASA dissolved in any of the above mentioned solvents at a concentration of 5–10% are available.

Reference: *Shinko-Lac ASA Weatherable and Heat Resistant ASA Resin*, Supplier design guide (9011-1000 (H) B), Mitsubishi Rayon Company, 1990.

BASF AG: Luran S (features: natural resin)

Luran S (ASA) articles can be bonded together by solvents such as 2-butanone, dichloroethylene, and cyclohexane. These solvents allow moldings made of different Luran S types to be bonded together and also Luran S articles to be bonded to Terluran (ABS) or Luran 378 P and 388 S (SAN).

Reference: *Luran S Acrylonitrile Styrene Acrylate Product Line, Properties, Processing*, Supplier design guide (B 566 e/10.83), BASF Aktiengesellschaft, 1983.

37.4.7 Adhesive Bonding

GE Plastics: Geloy XP1001-100

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load

Table 37.7. Achievable Strengths of Vibration Welds of Acrylonitrile-Styrene-Acrylate Copolymer (ASA) to Itself

Material Family	ASA
Tensile strength*, MPa (ksi)	32.5 (4.7)
Elongation @ break*, %	2.9
Specimen thickness, mm (in.)	6.3 (0.25)
Mating Material	
Material family	ASA
Tensile strength*, MPa (ksi)	32.5 (4.7)
Elongation @ break*, %	2.9
Specimen thickness, mm (in.)	6.3 (0.25)
Process Parameters	
Process type	Vibration welding
Weld frequency	120 Hz
Welded Joint Properties	
Weld factor (weld strength/virgin material strength)	0.46
Elongation @ break*, % (nominal)	0.9

*strain rate of $10^{-2}s^{-1}$.

Table 37.8. Luran S Product Combinations Suitable for Laser Welding

Transmitting Component	Absorbing Component
KR2864C	KR2864C
776 S	776 S or 2866 C
777 K	777 K or 757 G
757 G	777 K or 757 G
2861/1C	757 G or 2866 C
2864 C	777 K or 757 G
2863 C	2866 C
797 S	777 K or 2866 C

on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches/second (0.25 mm/s).

While the bond strengths in Table 37.9 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 37.9, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: The three cyanoacrylates tested, namely Black Max 380, Prism 401 and 4305, and Super Bonder 414 instant adhesives, as well as 3030 adhesive, all created bonds that were stronger than the substrate on almost all of the ASA formulations evaluated. Loctite 3105, a light curing acrylic adhesive, Speedbonder H3000 and H4500 structural adhesives, Hysol U-05FL urethane adhesive and Hysol 3631 hot melt adhesive did not achieve substrate failure, but did perform well on ASA. 3340 light cure adhesive, Hysol 3651 hot melt adhesive and 5900 flange sealant achieved the lowest bond strengths on ASA.

Surface Treatments: The effect of using Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, could not be determined because both primed and unprimed ASA achieved substrate failure for most of the formulations evaluated. Surface roughening had an inconsistent effect on the bondability of ASA.

Other Information: ASA can be stress-cracked by uncured cyanocrylate adhesives, so any excess adhesive should be removed from the surface immediately. ASA is compatible with acrylic adhesives but can be attacked by their activators before the adhesive has cured. Any excess activator should be removed from the surface immediately. ASA is incompatible with anaerobic adhesives. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

Mitsubishi Rayon: Shinko-Lac

For adhesion of Shinko-Lac ASA to woods or metals, adhesives made of neoprene or epoxy resins are recommended, depending on the applications.

Table 37.9. Shear Strengths of Geloy XP1001-100 ASA to ASA Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[b]

Material Composition		**Loctite Adhesive**					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive General Purpose)	**Depend 330** (Two-Part No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	4 rms	>1650[a] (>11.4)[a]	>1750[a] (>12.1)[a]	>1750[a] (>12.1)[a]	>1700[a] (>11.7)[a]	950 (6.6)	1300 (9.0)
Roughened	28 rms	>1650[a] (>11.4)[a]	>1900[a] (>13.1)[a]	1150 (7.9)	>1850[a] (>12.8)[a]	700 (4.8)	1300 (9.0)
Antioxidant	0.2% Irganox 245	>1650[a] (>11.4)[a]	>1750[a] (>12.1)[a]	>1750[a] (>12.1)[a]	>1700[a] (>11.7)[a]	950 (6.6)	1300 (9.0)
UV stabilizer	0.5% Tinuvin 770 0.5% Tinuvin P	>1300[a] (>9.0)[a]	>1750[a] (>12.1)[a]	>1750[a] (>12.1)[a]	>1700[a] (>11.7)[a]	950 (6.6)	1300 (9.0)
Flame retardant	20% F2016	>1650[a] (>11.4)[a]	>1750[a] (>12.1)[a]	>1750[a] (>12.1)[a]	>1700[a] (>11.7)[a]	650 (4.5)	1300 (9.0)
Impact Modifier	9% Paraloid EXL3330	>1650[a] (>11.4)[a]	>1750[a] (>12.1)[a]	>1750[a] (>12.1)[a]	>1850[a] (>12.8)[a]	950 (6.6)	1300 (9.0)
Lubricant	0.3% Mold Wiz INT SP8	>1650[a] (>11.4)[a]	>1750[a] (>12.1)[a]	>1750[a] (>12.1)[a]	>1700[a] (>11.7)[a]	950 (6.6)	1300 (9.0)
Colorant	1% OmniColor Nectarine	>1650[a] (>11.4)[a]	>1750[a] (>12.1)[a]	>1750[a] (>12.1)[a]	>1700[a] (>11.7)[a]	950 (6.6)	1300 (9.0)
Antistatic	1.5% Dehydat 93P	>1650[a] (>11.4)[a]	>1750[a] (>12.1)[a]	>1750[a] (>12.1)[a]	>1700[a] (>11.7)[a]	950 (6.6)	1300 (9.0)

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D 4501). Values are given in psi and MPa (within parentheses).

Reference: *Shinko-Lac ASA Weatherable And Heat Resistant ASA Resin*, Supplier design guide (9011-1000 (H) B), Mitsubishi Rayon Company, 1990.

37.4.8 Mechanical Fastening

Bayer: Centrex 833

Tapping and Self-tapping Screws: Table 37.10 lists some average pull-out forces and various torque data for thread-cutting screws tested in Centrex 833 ASA resin. For this data, the screws were installed in the manufacturer's suggested hole diameters. The screw boss outer diameter was approximately twice the screw outer diameter.

Reference: *Engineering Polymers. Joining Techniques. A Design Guide*, Supplier design guide (5241 (7.5M) 3/01), Bayer Corporation, 2001.

37.5 Styrene-Acrylonitrile Copolymer

37.5.1 General

BASF AG: Luran (features: transparent)

Luran extruded stock and moldings can be welded together by hot shoe, rotational, and ultrasonic techniques.

Reference: *Luran Product Line, Properties, Processing*, Supplier design guide (B 565 e/10.83), BASF Aktiengesellschaft, 1983.

37.5.2 Ultrasonic Welding

Bayer: Lustran SAN

At a frequency of 20 kHz, an amplitude of 15–30 μm is recommended for ultrasonic welding of Lustran SAN.

Table 37.10. Thread-cutting Screw Data for Centrex 833 ASA Resin

Screw Size & Type	Screw Length, in. (mm)	Hole Diameter, in. (mm)	Drive Torque, lb in. (Nm)	Recommended Tightening Torque, lb in. (Nm)	Stripping Torque, lb in. (Nm)	Screw Pull-Out, lb (N)
#6, Type 23	0.375 (9.5)	0.120 (3.0)	3.1 (0.35)	4.8 (0.54)	8.1 (0.92)	171 (760)
#6, Type 25	0.500 (12.7)	0.120 (3.0)	2.5 (0.29)	6.1 (0.69)	13.3 (1.51)	181 (803)
#6, Hi-Lo	0.750 (19.0)	0.115 (2.9)	2.8 (0.31)	8.0 (0.91)	18.5 (2.10)	279 (1242)
#8, Type 23	0.500 (12.7)	0.136 (3.5)	5.2 (0.59)	6.5 (0.74)	9.2 (1.03)	272 (1209)
#8, Type 25	0.562 (14.3)	0.146 (3.7)	3.6 (0.41)	9.0 (1.01)	19.7 (2.22)	405 (1800)

Reference: *Ultrasonic Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

Dow Chemical: Tyril 880B (note: high acrylonitrile content); **Tyril 990** (note: low acrylonitrile content)

This study was designed to identify which resins could be effectively welded to themselves and other resins, and to identify the maximum bond integrity. Besides looking at the weld strength of various thermoplastic resins, this study explores the effects of gamma radiation and EtO sterilization on the strength of these welds. A wide variety of resins used in the healthcare industry were evaluated including styrene acrylonitrile (SAN).

The strength of customized "I" beam test pieces was tested in the tensile mode to determine the original strength of each resin in the solid, non-bonded test piece configuration. Data from this base-line testing was used to determine the percent of original strength that was maintained after welding. The most commonly used energy director for amorphous resins, a 90° butt joint, was used as the welding architecture.

Every attempt was made to make this a "real world" study. The aim during the welding process was to create a strong weld, while maintaining the aesthetics of the part. One of the most important factors in determining whether or not a good weld had been achieved was the amount of flash, or overrun noticed along both sides of the joint. Another characteristic of a good weld was a complete wetting of the cross-sectional weld area. The problem here, however, was that only clear polymers used as the top piece, allowed the whole weld to be seen.

Overall, it appeared resin compatibility and the ability to transfer vibrational energy through a part and not close glass transition temperatures, were the overriding characteristics that led to the best welds. Although not shown in this study, it should be noted that the ability for a resin to be welded is also a function of the architecture of the ultrasonic weld. Some resins that welded well in the architecture used for this study may not weld well with other architectures.

The SAN resins ultrasonically bonded, in some fashion, to all the resins in this study. Due to the extreme notch sensitivity of SAN, numerous premature failures occurred during the strength testing. This was most evident in bonds with other brittle polymers such as GPPS. This problem could possibly be eliminated by changing the test-piece design. However, from a "real world" perspective, this may be a phenomenon to keep in mind when designing parts that involve SAN.

The SAN grade with the lower acrylonitrile (AN) content showed a tendency to produce ultrasonic bonds with higher strengths overall versus the higher AN content grade. On the other hand, the low AN grade showed a tendency to lose strength after EtO sterilization, whereas the high AN grade did not show this same trend. It is well known that AN imparts improved chemical resistance in styrenic polymers. This explains why the higher AN content resin provides a better barrier to EtO attack. Gamma sterilization didn't seem to affect the SAN bond integrity during this short-term study.

Reference: Kingsbury RT: Ultrasonic weldability of a broad range of medical plastics. ANTEC 1991, Conference proceedings, Society of Plastics Engineers, Montreal, May 1991.

Dow Chemical: Tyril (features: transparent)

Excellent results are obtained by sonic welding parts molded with Tyril to each other, and also to parts molded of ABS.

Reference: *Tyril SAN Resins Engineering and Fabrication Guidelines*, Supplier design guide (301-01318-290 RID), Dow Chemical, 1990.

37.5.3 Solvent Welding

Dow Chemical: Tyril (features: transparent)

Parts made of Tyril resins may be welded to each other with a number of effective solvents. Methylene chloride is commonly used if a fast drying solvent is desired. MEK and a mixture of 30% methyl methacrylate monomer and 70% butyl acetate, are effective medium drying solvents. To add body, these solvents can accept up to 15% (wt.) of pellets of Tyril resin.

Reference: *Tyril SAN Resins Engineering and Fabrication Guidelines*, Supplier design guide (301-01318-290 RID), Dow Chemical, 1990.

Dow Chemical: Tyril (features: transparent)

In tests conducted to evaluate the bondability/compatibility of plasticized PVC tubing to rigid, transparent thermoplastics, results suggest to avoid straight MEK or blends with high amounts of methylene chloride for use with SAN. Crazing was quite pronounced when straight methylene chloride or acetone were used as solvents. The SAN luers tested with surprisingly high peak loads. Results suggest that the solvent of choice for SAN is a blend of MEK in cyclohexanone in ratios ranging between 10:90 and up to 50:50.

Reference: Haskell A: Bondability/compatibility of plasticized PVC to rigid, transparent thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

BASF AG: Luran (features: transparent)

When bonding with solvents, the difference in the resistance of the Luran grades to aromatic hydrocarbons becomes noticeable. While Luran 358 N and 368 R can be readily bonded with toluene, Luran 378 P and 388 S require the use of more powerful solvents, such as ethyl acetate, dichloroethylene, and cyclohexanone. Parts made from Luran 358 N and 368 R as well as Luran 378 P to 388 S can only be reliably bonded using solvents to parts made from the same material, or to parts made from the same group.

Reference: *Luran in Processing*, Supplier design guide, BASF Aktiengesellschaft.

Cheil Industries: Starex

Solvent welding is typically practiced with various solvents such as MEK, acetone, styrene monomer, and trichloroethylene. It is also desirable to solute about 5% of SAN resin with these chemicals.

Reference: *Starex SAN*, Supplier design guide, Cheil Industries.

37.5.4 Adhesive Bonding

Monsanto: Lustran 31

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches/second (0.25 mm/s).

While the bond strengths in Table 37.11 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 37.11, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive

Table 37.11. Shear Strengths of Lustran 31 SAN to SAN Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[b]

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive General Purpose)	**Depend 330** (Two-Part No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	3 rms	500 (3.5)	>3800[a] (>26.2)[a]	450 (3.1)	>3650[a] (>25.2)[a]	800 (5.5)	2800 (19.3)
Roughened	18 rm	>850[a] (>5.9)[a]	>3800[a] (>26.2)[a]	1150 (7.9)	>3650[a] (>25.2)[a]	800 (5.5)	>2900[a] (>20.0)[a]
UV stabilizer	0.31% Tinuvin 770 0.31% Tinuvin 328	>2050[a] (>14.1)[a]	>3800[a] (>26.2)[a]	450 (3.1)	>5950[a] (>41.0)[a]	>1200[a] (>8.3)[a]	2800 (19.3)
Flame retardant	4% Saytex HBCD-SF 1% Antimony Oxide	500 (3.5)	1850 (12.8)	>1000[a] (>6.9)[a]	1550 (10.7)	800 (5.5)	>2800[a] (>19.3)[a]
Impact modifier	29% Paraloid EXL3330	1000 (6.9)	>3800[a] (>26.2)[a]	>1450[a] (>10.0)[a]	>3650[a] (>25.2)[a]	>1100[a] (>7.6)[a]	2800 (19.3)
Lubricant	0.1% Calcium Stearate 24–46	500 (3.5)	>3800[a] (>26.2)[a]	>750[a] (>5.2)[a]	>3650[a] (>25.2)[a]	800 (5.5)	2800 (19.3)
Internal mold release	5% Mold Wiz INT-33PA	750 (5.2)	>3800[a] (>26.2)[a]	450 (3.1)	>3650[a] (>25.2)[a]	800 (5.5)	1750 (12.1)
Glass filler	17% Glass Type 3540	500 (3.5)	>3800[a] (>26.2)[a]	450 (3.1)	>4550[a] (>31.4)[a]	800 (5.5)	2800 (19.3)
Colorant	1% OmniColor Fuschia	500 (3.5)	>3800[a] (>26.2)[a]	1400 (9.7)	>3650[a] (>25.2)[a]	>900[a] (>6.2)[a]	2800 (19.3)
Antistatic	3% Armostat 550	>1850[a] (>12.8)[a]	>3800[a] (>26.2)[a]	450 (3.1)	>3650[a] (>25.2)[a]	800 (5.5)	>3000[a] (>20.7)[a]

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D 4501). Values are given in psi and MPa (within parentheses).

that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 and Super Bonder 414 instant adhesives and Flashcure 4305 light cure adhesive, created bonds stronger than the SAN substrate for all the formulations evaluated, with the exception of the formulation containing the flame retardant additive. Loctite 3105, a light curing acrylic adhesive and Loctite 3030 adhesive achieved the second-highest bond strengths. The overall bondability of all the tested adhesives on various grades of SAN is very good, with the exceptions being Loctite 3651 and Hysol 7804 hot melt adhesives.

Surface Treatments: Surface roughening caused either no effect, or a statistically significant increase in the bond strengths achieved on SAN. The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused a statistically significant decrease in the bond strengths achieved on SAN for all the formulations that were evaluated.

Other Information: SAN is compatible with acrylic adhesives but can be attacked by their activators before the adhesive has cured. Any excess activator should be removed from the surface immediately. SAN is incompatible with anaerobic adhesives. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier Design guide, Loctite Corporation, 2006.

Bayer: Lustran SAN

UV-cured adhesives, excellent for transparent materials such as Lustran SAN, cure in seconds and typically have high bond strength. Two-part acrylic adhesives usually show high bond strength.

Reference: *Engineering Polymers. Joining Techniques. A Design Guide*, Supplier design guide (5241 (7.5M) 3/01), Bayer Corporation, 2001.

Dow Chemical: Tyril (features: transparent)

Many common rubber-based adhesives may be used to bond parts made with Tyril to a variety of nonplastic materials such as metal, wood, and glass. Similarly, successful adhesive bonds can be made between parts of Tyril and parts molded of plasticized PVC, Saran resin or cellulosics.

Note: polystyrene parts are very difficult to adhesive-bond to those same plastics. Where this is a problem, molding the part of Tyril can be an effective answer. In choosing the adhesive, test to be certain there will be no bonded part failure caused by stress cracking.

Reference: *Tyril SAN Resins Engineering and Fabrication Guidelines*, Supplier design guide (301-01318-290 RID), Dow Chemical, 1990.

37.6 Styrene-Maleic Anhydride Copolymer

37.6.1 General

Arco: Dylark

All Dylark resins work very well with a multitude of assembly procedures including mechanical fastening, solvents, adhesives, spin welding, ultrasonic welding, and vibration welding.

Any technique that creates a melting of the joint surface of the Dylark parts can usually be successfully employed in assembly operations. Vibrations to create frictional heat are useful for joining large parts. Spin welding, which develops frictional heat by rotating one Dylark resin part against another is useful for round parts. Hot plate or fusion welding uses a heated surface, momentarily in contact with the mating surfaces to create the weld with localized melting. Heat staking (or swaging) uses a heated platen or probe to flatten a stake or deform an edge to create an assembly. Elecromagnetic induction welding (EMI) creates melting and welding through controlled electromagnetic heating of metal particles within a special plastic gasket applied to the joint interface.

Reference: *DYLARK Engineering Resins Design Guide*, Supplier design guide (ACC-P120-882), ARCO Chemical Company, 1988.

37.6.2 Ultrasonic Welding

Bayer: Cadon

At a frequency of 20 kHz, an amplitude of 25–40 µm is recommended for ultrasonic welding of Cadon SMA copolymer.

Reference: *Ultrasonic Welding*, *Supplier Design Guide*, Bayer MaterialScience AG, 2007.

Arco: Dylark

Dylark resin parts may be rapidly and economically joined to each other and to other amorphous thermoplastics with similar melting temperatures using ultrasonic equipment.

Ultrasonic equipment is also used for staking and spot welding of Dylark resin parts.

Reference: *DYLARK Engineering Resins Design Guide*, Supplier design guide (ACC-P120-882), ARCO Chemical Company, 1988.

37.6.3 Vibration Welding

Arco: Dylark 480P16 (form: extruded sheet; reinforcement: 16% glass fiber)

Strengths of about 29.5 MPa (4280 psi) were attained, which is only about 35% of the parent material strength. The failure strains were about 0.96%. Higher strengths were obtained at low weld pressures (0.52 and 0.9 MPa; 75 and 131 psi); the weld strengths were lower at higher weld pressures. The attainable weld strengths and the failure strains were both marginally higher for 6.35 mm (0.25 inch) thick specimens compared to 3.2 mm (0.126 inch) thick specimens.

T-joints had substantially lower strengths than butt joints. For the 6.35 mm (0.25 inch) thick specimens, the highest T-joint strength (17.7 MPa; 2570 psi) is only about 61% of the highest strength of butt welds (28.9 MPa; 4190 psi).

Reference: Stokes VK: Vibration welding of glass-filled poly(styrene-co-maleic anhydride). *Journal of Adhesion Science and Technology*, 15(10), p. 1213, 2001.

37.6.4 Solvent Welding

Nova Chemicals: Dylark

Solvent types that are suitable for use with Dylark are MEK, methylene chloride (dichloromethane), xylene (xylol) and toluene (toluol). In general, solvents that work well with other styrenic polymers and polycarbonate can also be used with Dylark.

Reference: *DYLARK, Design for Assembly*, Supplier design guide, Nova Chemicals.

Arco: Dylark

Several solvents can be effectively used to join together parts molded in Dylark resin with similar parts or with parts molded from other plastic materials. The principle involved is to use a solvent that will dissolve the surface of the mating parts sufficiently to allow the parts to be joined together after the solvent has evaporated. A key advantage of this method is that it is fast, usually no joint surface preparation is required, and the final joint does not depend upon chemical bonding of a separate adhesive material.

The key limitation of solvent welding is the precautions that must be taken in handling the solvents. Federal, EPA, and local regulations must be observed regarding ventilation, worker protection, and solvent recovery.

Solvents such as methylene chloride (dichloromethane) or MEK, which work well with polystyrene, ABS, and polycarbonate also work well with all Dylark resins. A thicker, slower evaporating solvent cement can be prepared by dissolving 10–20% Dylark resin into the solvents.

Reference: *DYLARK Engineering Resins Design Guide*, Supplier design guide (ACC-P120-882), ARCO Chemical Company, 1988.

37.6.5 Adhesive Bonding

Nova Chemicals: Dylark

Adhesive families that work best with Dylark are those that are either acrylic-, cyanoacrylate-, or methacrylate-based. Caution should be taken in using anaerobic-based adhesive in that these are typically incompatible with polystyrene type materials. One of the key factors is good wet out of the adhesive to fill any irregularities in the substrate surface. This is essential for developing strong and reliable bonds. Some commercial adhesives that can be used with Dylark include Loctite Depend 330 and Loctite Prism 401.

Reference: *DYLARK—Design for Assembly*, Supplier design guide, Nova Chemicals.

Arco: Dylark

Parts molded in Dylark resin may be bonded to other plastic parts, metals, ceramics, glass, and most other substances using a variety of commercially available adhesives. In general, epoxies, polyurethanes, and acrylics work very well with molded Dylark resin parts. Silicone rubber adhesive/sealants (RTV) and cyanoacrylates (instant adhesives) have also been successfully used with Dylark resins.

Cleaning and surface preparation is important with all adhesives since they must make intimate contact with the part surface for maximum adhesive strength. The preparation, mixing, application, and safety recommendations from the adhesive manufacturer must be followed.

Reference: *DYLARK Engineering Resins Design Guide*, Supplier design guide (ACC-P120-882), ARCO Chemical Company, 1988.

37.6.6 Mechanical Fastening

Nova Chemicals: Dylark

Clips/Rivets: Holes and slots can be molded into a Dylark instrument panel and console substrates for use with metal clips, push-nuts, and screw in plastic nut inserts. Round holes can also be drilled into instrument panel substrates. Molded-in slots or square holes should be clean and free of stress risers with adequate radii and wall stock.

Staples: Stapling can be an alternative method for fastening various items to Dylark that would require minimal pull strength or shear load. Common applications that utilize staples as a fastening method include attaching parts less functional or assembling carpeting to Dylark substrates. The following is recommended for use with staples:

- Maintain the recommended 0.50 inch (13 mm) or greater distance from any edge.
- Utilize a chisel-shaped design versus a wedge-shaped design. This allows the plastic to be punched through the material instead of splitting the material causing fractures in the part.
- Parts should be well supported in areas that are being stapled to minimize flexing of the parts. The use of nests or fixtures is recommended.

Reference: *DYLARK—Design for Assembly*, Supplier design guide, Nova Chemicals.

Arco: Dylark

Mechanical fastening systems are commonly used when assembling molded Dylark resin parts to metal parts, mechanical devices, electrical, or electronic components, or other plastic parts. The key consideration in mechanical fastening, usually with metal fasteners, is that the part molded in Dylark resin does not become over-stressed due to improper installation, excessive loads, or poor joint design.

Although tapped threads and molded threads can be used with Dylark resin parts, the most prevalent fastening systems use various types of self-tapping screws, common bolts and nuts, threaded metal inserts, and rivets.

In a typical bolted assembly, both the male and female threads are made from steel or other metal. Because of the relatively high strength of these fasteners, it is likely that the plastic parts can become over-stressed well before the fasteners will strip. In general, these problems can be avoided with molded Dylark resin parts by following certain good design practices:

- The area under the fastener which bears on the plastic part should be kept large enough to distribute the clamping load and applied forces. This is usually done with large head screws, flanged nuts, or washers. This will help to avoid stresses that could cause fracture or long-term relaxation problems (Fig. 37.2).
- Assemblies involving Dylark resin parts should be so designed that the plastic part bottoms against a supporting member before extensive deformation occurs. This avoids unnecessary high bending stresses.
- The assembly torque should be controlled with the use of automatic torque-controlled wrenches. Where assembly torque cannot be controlled, or must be high for other reasons, stepped washers or shoulder screws can be very effective, since the axial force exerted on the plastic part is limited by the metal to metal contact (Fig. 37.3).
- Flat head screws should be avoided unless the assembly torque can be accurately controlled. The wedging action from the tapered underside of the head can easily create damaging stresses. If the screw head must be below the surface, a pan-head screw and a counterbored hole is preferred.

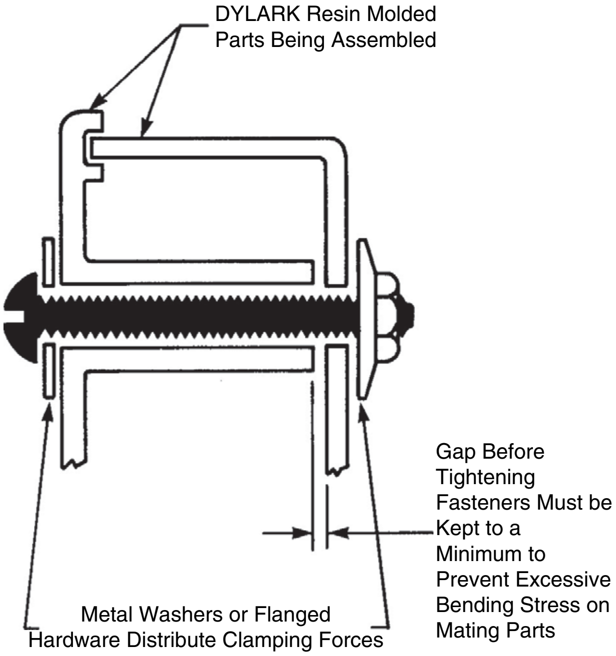


Figure 37.2. Bolted assembly, Dylark styrene maleic anhydride copolymer.

Tapping and Self-tapping Screws: In a wide variety of applications, molded Dylark resin parts are used in assemblies that are put together only once. In these cases, or when only a few disassembly and assembly operations are anticipated, self-tapping screws work very well. There are many types of self-tapping screws. Some cut the thread, some cold-form the thread, and some do a combination of both. Generally, the thread-cutting variety are preferred with Dylark resin parts since they tend to exert less hoop stress on the boss

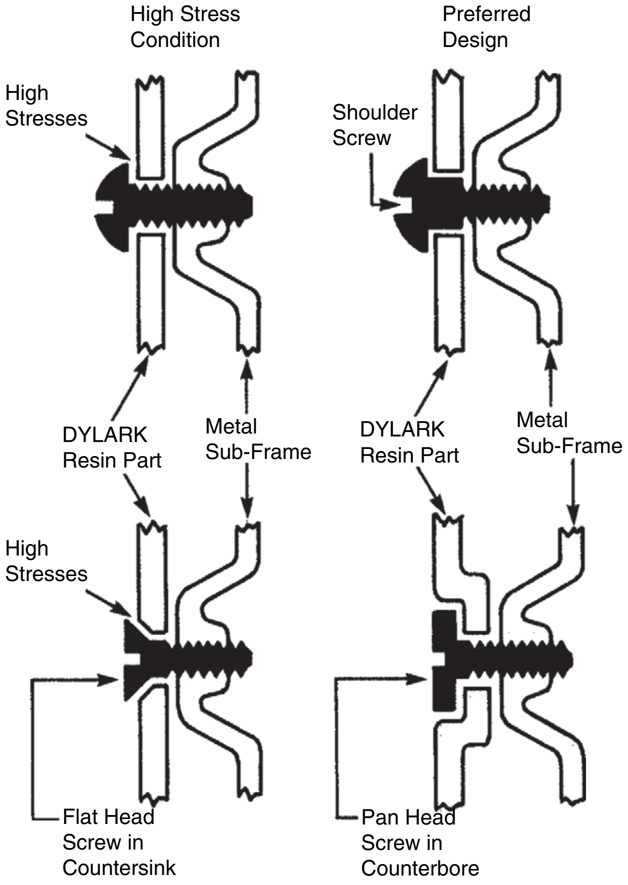


Figure 37.3. Managing stress levels in the plastic part when assembly torque cannot be controlled, Dylark styrene maleic anhydride copolymer.

than the thread-forming type. A wide variety of self-tapping screws are specifically designed for plastic parts. These screws are well-suited for high volume, assembly line production, have excellent pull-out resistance, and do not over stress a properly designed Dylark resin boss.

As with all mechanical fasteners, torque should be controlled to acceptable limits, the boss must be sized properly to handle the screw installation stresses as well as the applied loads, and the bearing areas under the screw heads must be adequate (Fig. 37.4).

Oils used on screws for protection or lubricity can adversely affect the end-use performance of engineering resins. Dylark resins have demonstrated superior performance under end-use conditions with and without applied strain. Testing with the specific screw oil is suggested.

Threaded Mechanical Inserts: Since it is often inconvenient and uneconomical to use loose machine nuts in plastic part assemblies, threaded metal inserts are usually used when frequent disassembly and reassembly is required. This also avoids cross-threading which could occur if self-tapping screws are disassembled and then reassembled. The same basic considerations used with bolted assemblies must be observed. In addition, the strength of the mounting boss must be considered.

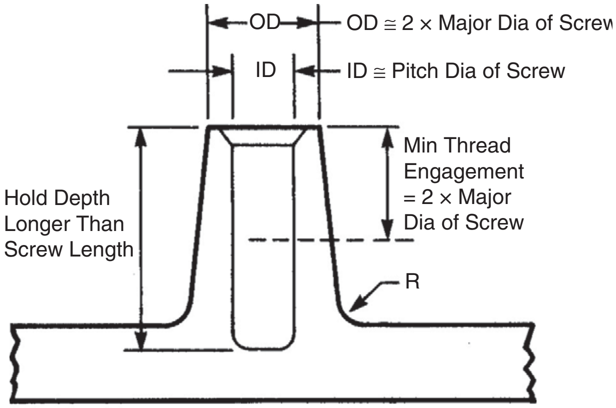
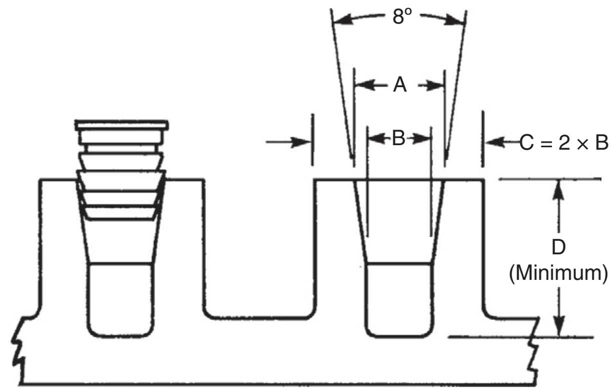


Figure 37.4. Boss design guidelines for self-tapping screws, Dylark styrene maleic anhydride copolymer.

There are many types of threaded metal inserts that can be used with Dylark resin. Where ultrasonic equipment is not available or can't be used, similar threaded metal inserts can be installed by heating the insert. Others are designed to push in, spin in, or expand after insertion when the mating screw is installed. Some of these inserts can create high hoop stresses in the accepting boss; they should be used with adequate boss design and checked with final product testing. Where assembly requirements are less demanding, boss caps, which go over the boss, can provide an economical metal thread which actually reinforces the boss against the expansion that might be created by a self-tapping screw.

Ultrasonic Inserts: Ultrasonic insertion is a fast, economical, and reliable method for installing permanent metal threads in molded Dylark resin parts. Inserts can often be inserted right at the molding machine by the machine operator. In properly designed Dylark resin bosses (Fig. 37.5), ultrasonically-installed inserts result in low residual stress since the plastic uniformly melts around the insert during insertion.

Reference: *DYLARK Engineering Resins Design Guide*, Supplier design guide (ACC-P120-882), ARCO Chemical Company, 1988.



Thread Size	Insert OD"	Length"	Lead-In Dia A"	Diameter B"	Minimum Depth D"
4–40	0.171	1/4	0.160	0.136	5/16
6–32	0.217	5/16	0.210	0.177	3/8
8–32	0.250	3/8	0.240	0.200	7/16
10–32	0.295	7/16	0.280	0.235	1/2
1/4–20	0.375	1/2	0.355	0.325	5/8

These are typical values. Since ultrasonic inserts vary in size and design, contact manufacturer of inserts for their recommendations.

Figure 37.5. Typical boss hole design for the use of ultrasonically installed inserts, Dylark styrene - maleic anhydride copolymer.

37.7 Styrene-Butadiene Copolymer

37.7.1 General

BASF AG: Styrolux (features: transparent)

Styrolux can be welded by hot shoe, thermal impulse, ultrasonic, vibration, and rotational techniques. The level of mechanical properties and the quality of the welds can be influenced in all the techniques adopted by judicious selection of the product and by optimizing the welding parameters. Other factors that affect the results are the previous history of the parts to be welded together and the design of the contacting surfaces.

Reference: *Styrolux Product Line, Properties, Processing*, Supplier design guide (B 583 e/(950) 12.91), BASF Aktiengesellschaft, 1992.

37.7.2 Ultrasonic Welding

BASF AG: Styrolux 656 C (features: high flow, 0.1 mm (0.004 inches) thick; form: film); **Styrolux 684 D** (features: 0.1 mm (0.004 inches) thick; form: film)

Figures 37.6 and 37.7 show how the strength of the weld can be influenced by varying the machine

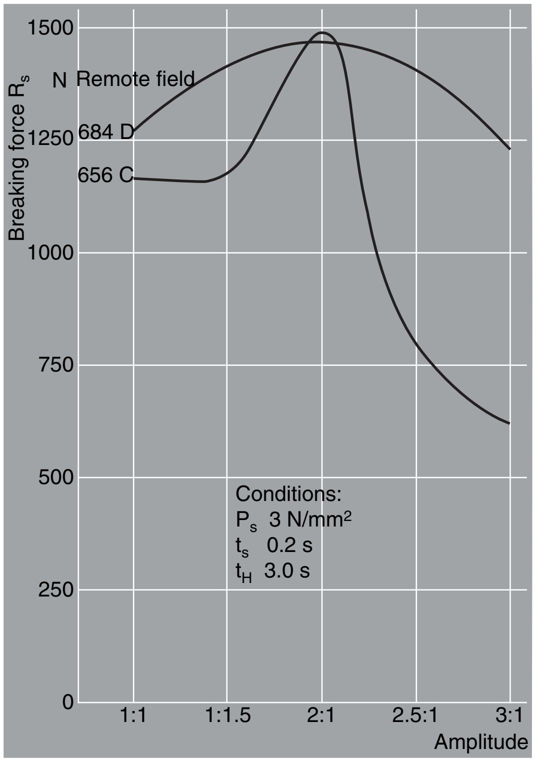


Figure 37.6. Effect of ultrasonic welding amplitude on the strength of Styrolux styrene-butadiene block copolymer.

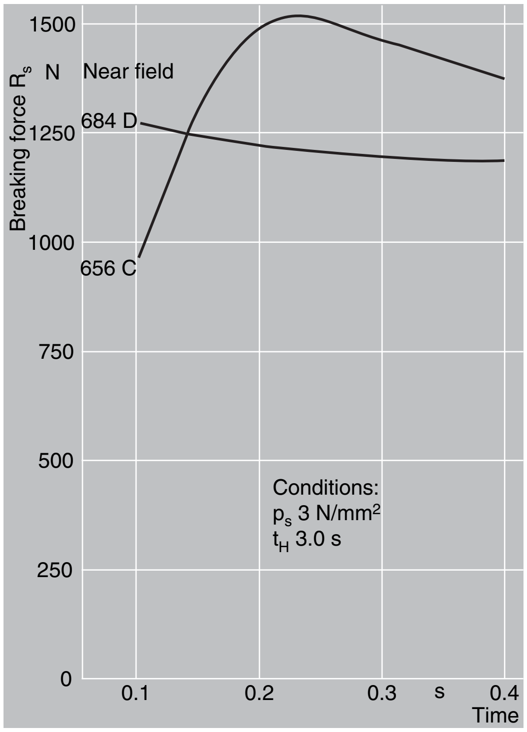


Figure 37.7. Effect of ultrasonic welding time on the strength of Styrolux styrene-butadiene block copolymer.

parameters in ultrasonic welding. A comparison of the amplitudes in remote radiation field welding is shown. An unsuitable amplitude transformation of 3:1 can reduce the strength of the weld by about 60%. The relationship between weld strength and welding time in near field welding is also shown.

37.7.3 Solvent Welding

Phillips: K-Resin KR01 (features: transparent)

In tests conducted to evaluate the bondability/compatibility of plasticized PVC tubing to rigid, transparent thermoplastics, the peak loads for several solvents used to bond styrene-butadiene copolymer to the tubing were classified as marginal in spite of 11–12 lbf (5.0–5.4 kgf) values. This is due to high variances, which cannot insure that all bonds could withstand the 10 lbf (4.5 kgf) pull test. Styrene-butadiene did give satisfactory bonds when any cocktail containing cyclohexanone was used. Each solvent allowed for easy assembly, with the exception of acetone, which was also the only solvent to cause crazing. The results suggest that the optimal solvent for styrene-butadiene is a 80:20 blend of methylene chloride in cyclohexanone.

Reference: Haskell A: Bondability/compatibility of plasticized PVC to rigid, transparent thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

38 Sulfone-Based Resins

38.1 Polyethersulfone

38.1.1 General

BASF AG: Ultrason E (features: transparent, amber tint)

Unbreakable connections between Ultrason moldings can be formed by the various welding techniques. Adhesives are resorted to for effecting firm bonds between Ultrason and other materials. Other means of forging unbreakable connections are riveting and beading.

Detachable bonds can be formed by snap-on connectors, screws, and bolts. The threads may be formed during the molding process or may assume the form of metal inserts that are subsequently fixed, for example, by ultrasonic techniques, in recesses provided for them in the moldings.

The conventional welding techniques adopted for thermoplastics are suitable for the various Ultrason products. The only exception is high frequency welding, which is unsuitable for thermoplastics with low dissipation factors. If the Ultrason moldings have picked up moisture, which is usually the case, it is absolutely essential to dry them before welding in order to avoid foaming in the zone of the weld during the melting phase.

The welding technique to be adopted depends on the geometry of the moldings and the stress pattern. Allowance must be made for the fact that molded-in stresses cannot be completely avoided, especially in moldings with very thick walls produced from Ultrason or any other material. Examples of Ultrason welded to other materials are in Table 38.1.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide (B 602 e/10.92), BASF Aktiengesellschaft, 1992.

Table 38.1. Welding Techniques for Joining Ultrason Polyethersulfone to Other Materials

Material	Suitable Technique
Textiles	Ultrasonic welding
(Pretreated) metal foil	Heated tool welding
Other plastics e.g., PBT, ASA and ABS	Ultrasonic welding

38.1.2 Heated Tool Welding

PES (reinforcement: glass fiber); **PES** (features: unfilled)

This study concluded the following concerning heated tool welding of polyethersulfone:

- After aging in air, tensile properties of the welds deteriorated faster than the parent material. Retention of the strength of the parent material was higher for the unreinforced than the reinforced grades when aged at 230°C (446°F). Retention of tensile properties was higher for reinforced grades as compared with unreinforced grades.
- Cross-sectional areas in unreinforced PES welds decreased by about 17% and for reinforced PES welds increased by about 5% after 4 weeks aging at 220°C (428°F). For parent materials, there was an increase of 9–12% for both.
- After immersion in boiling water for 2 weeks, the strength of both unreinforced and reinforced PES parent materials and unreinforced welds changed only slightly.
- After water immersion tests, there was very little effect on both cross-sectional area and weight of welds and parent materials (<2%).
- Dynamic mechanical thermal analysis showed an increase in Tg of the weld aged in air at 230°C (446°F). The Tg of the hot plate weld increased from 237°C (459°F) to 244°C (471°F) after 7 days aging at 230°C (446°F). The Tg of the aged parent material was unaffected.
- Fractographic examination of both welds and parent materials indicated that aging was associated with the formation of internal cavities. The number and size of cavities increased with the severity of degradation. For reinforced PES, tensile fracture was associated with predominantly matrix failure after air aging and interfacial failure after immersion in boiling water.

Reference: Tavakoli SM: Effects of ageing on tensile properties and structure of linear friction and hot plate welds in polyethersulphone. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

PES (material composition: 30% glass fiber reinforcement)

An examination of a heated tool weld for 30% glass reinforced PES shows a large amount of melt flow in the welding upset causing an orientation of the fibers parallel to the joining zone. In addition, air bubbles are evident in the seam, caused by the material sticking to the heated tool after the heating phase. For heated tool welding, the maximum welding factor (strength of weld/ strength of bulk material) is 0.62 for the 30% glass reinforced PES.

Reference: Potente H, Natrop J, Pedersen TK, Uebbing M: Comparison of three methods for welding glass-fibre reinforced PES. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

BASF AG: Ultrason E (features: transparent, amber tint)

Ultrason necessitates high tool temperatures, for which conventional non-stick layers are unsuitable. In heat contact methods, the tool must be cleaned continuously to remove adhering residues.

Owing to the high temperatures involved, a very brief change-over period, if possible less than one second, is required to prevent the surface of the melt from cooling to a temperature below the melting point. Excellent results have been obtained with the following parameters:

- heated tool temperature 380–550°C (716–1022°F)
- heating-up period 10–90 seconds
- specific joining pressure 2–5 MPa (290–725 psi)

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

38.1.3 Ultrasonic Welding

BASF AG: Ultrason E (features: transparent, amber tint)

Ultrasonic welding is recommended for parts with cross-sectional areas of 200 cm^2 (31 $inches^2$) or less or for welds of up to 10 cm^2 (1.6 $inches^2$) area. Larger parts necessitate two or more welding operations, which are performed simultaneously or one after the other. The short time required for welding, viz. two seconds, permits extremely rapid cycling. The geometry of the weld must conform to the requirements for ultrasonic welding. The welding parameters depend on the material and the design of the molding, and particularly good results have been achieved with the following settings:

- frequency 20–40 kHz
- amplitude 20–60 μm
- welding time 0.1–2.0 seconds
- specific welding pressure 1–5 MPa (145–725 psi)

The attainable joint efficiency, that is, the ratio of the strength of the weld to that of the material, lies between 0.3 and 0.6, the actual figure depending on the material and the design of the molding.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

38.1.4 Vibration Welding

PES (reinforcement: glass fiber); **PES** (features: unfilled)

This study concluded the following concerning vibration welds of polyethersulfone:

- After aging in air, tensile properties of the welds deteriorated faster than the parent material. Retention of the linear friction welds and parent material was higher for the unreinforced than the reinforced grades when aged at 230°C (446°F).
- The cross-sectional areas of the linear friction welds increased for both unreinforced (about 5%) and reinforced (11%) grades after 4 weeks aging at 220°C (428°F). For parent materials, there was an increase of 9–12% for both.
- After immersion in boiling water for 2 weeks, there was a 25% drop in strength of reinforced linear friction welds, whereas the strength of the unreinforced grade did not change significantly. The strength of both unreinforced and reinforced PES parent materials changed only slightly after the same period.
- After water immersion tests, there was very little effect on both cross-sectional area and weight of welds and parent materials (<2%).
- Fractographic examination of both welds and parent materials indicated that aging was associated with the formation of internal cavities. The number and size of cavities increased with the severity of degradation. For reinforced PES, tensile fracture was associated with predominantly

> matrix failure after air aging and interfacial failure after immersion in boiling water.

Reference: Tavakoli SM: Effects of ageing on tensile properties and structure of linear friction and hot plate welds in polyethersulphone. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

PES (material composition: 30% glass fiber reinforcement)

An examination of a vibration weld for 30% glass reinforced PES shows that the joining zone is narrow compared with hot plate or IR welding processes. The fibers are not only rearranged by the flow of melt but are aligned in the direction of the seam. For vibration welding, the maximum welding factor is 0.65 for the 30% glass reinforced PES.

Reference: Potente H, Natrop J, Pedersen TK, Uebbing M: Comparison of three methods for welding glass-fibre reinforced PES. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

BASF AG: Ultrason E (features: transparent, amber tint)

The amplitude required for heating the surfaces to be joined depends on the frequency of the machine, for example,

- 100 Hz: 1.0–4.0 mm (0.039–0.157 inches)
- 240 Hz: 0.5–2.0 mm (0.020–0.079 inches)

The welding time should be about 2–10 seconds; and the specific welding pressure, about 1–2 MPa (145–290 psi). Joint efficiencies of 0.4 can be achieved for unreinforced Ultrason resins; and of 0.2, for products containing 20% glass fiber reinforcement.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

38.1.5 Spin Welding

BASF AG: Ultrason E (features: transparent, amber tint)

Spin welding is suitable for Ultrason moldings that have been designed accordingly. The joint efficiencies that can be attained are similar to those achieved in vibration welding.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

38.1.6 Hot Gas Welding

BASF AG: Ultrason E (features: transparent, amber tint)

Hot air welding is suitable for joining large or complicated parts. The air temperature necessary lies between 450 and 500°C (842 and 932°F), and the diameter of the welding rod should correspond to the wall thickness of the molding. This technique is mostly adopted for manual welding and allows V-seams with joint efficiencies as high as 0.7 to be achieved on unreinforced Ultrason panels.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

38.1.7 Laser Welding

BASF: Ultrason E

Ultrason E2010 (transmitted part) can be laser welded to Ultrason E2010 sw 10018 (absorbing part).

Reference: *Transmission Laser-Welding of Thermoplastics*, Technical Information (WIS 0003 e 01.2001), BASF Aktiengesellschaft, 2001.

38.1.8 Infrared Welding

PES (material composition: 30% glass fiber reinforcement)

The difficulty encountered in welding glass fiber reinforced materials stems from the re-orientation of the fibers in the weld seam. A comparison of three welding processes (heated tool welding, vibration welding and radiant heater welding) was made to determine the best method for welding a thermoplastic with 30% glass fiber. Of the processes employed in this study, the best results were achieved with radiant heater welding. The main advantage of radiant heater welding for joining fiber reinforced thermoplastics lies in the non-contact heating. The fibers do not undergo any re-orientation until the joining phase.

An examination of a photograph of a radiant heater weld for 30% glass reinforced PES clearly shows that the fibers do not undergo such a pronounced re-orientation as with vibration and heated tool welding. There is evidence of a thick layer of melt. Fibers that have retained their original orientation in the center of the weld can be seen. In addition, there are no air bubbles in the weld zone. For radiant heater welding, the maximum welding factor is 0.85 for the 30% glass reinforced PES.

Reference: Potente H, Natrop J, Pedersen TK, Uebbing M: Comparison of three methods for welding glass-fibre reinforced PES. ANTEC 1994, Conference proceedings, Society of Plastics Engineers, San Francisco, May 1994.

BASF AG: Ultrason E (features: transparent, amber tint)

Since, in heat contact methods, the tool must continuously be cleaned to remove adhering residues, preference should be given to IR welding. The spacing between the parts to be welded and the heated tool should be about 0.2–0.6 mm (0.008–0.024 inches).

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide (B 602 e/10.92), BASF Aktiengesellschaft, 1992.

38.1.9 Solvent Welding

BASF AG: Ultrason E (features: transparent, amber tint)

Ultrason can also be bonded with solvents such as N-methyl-2-pyrrolidone (NMP), N,N-dimethylformamide and dichloromethane. Allowance must be made for the fact that these solvents may give rise to environmental stress cracking in parts that are subjected to mechanical stress. Their viscosity can be raised by adding 3–15% of Ultrason. In any event, the bonds must be allowed sufficient time to dry, that is, for complete removal of the solvent.

The strength of the bonds depends not only on the solvent but also on the geometry of the joints. Good results are obtained with tongue-and-groove joints. If the overlap is sufficiently long, these joints can transmit more than 60% of the assembly's strength.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

38.1.10 Adhesive Bonding

BASF: Ultrason E2010

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 38.2 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 38.2 so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Loctite 3105, a light curing acrylic adhesive, consistently achieved the highest bond strengths on PES, while Flashcure 4305 light cure adhesive achieved substrate failure at a lower bond strength. Prism 401 and Super Bonder 414 instant adhesives, Loctite 3030 adhesive, Hysol E-214HP epoxy adhesive, Hysol 3631 hot melt adhesive and Fixmaster high performance epoxy adhesive all developed significant bond strength on unfilled PES.

Surface Treatments: Surface roughening caused either no effect or a statistically significant increase in

Table 38.2. Shear Strengths of Ultrason E2010 PES to PES Adhesive Bonds Made Using Adhesives Available from Loctite Corporation*

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	5 rms	650 (4.5)	1600 (11.0)	150 (1.0)	950 (6.6)	250 (1.7)	3050 (21.0)
Roughened	24 rms	1850 (12.8)	1600 (11.0)	1100 (7.6)	1250 (8.6)	250 (1.7)	3050 (21.0)
Lubricant	9% Polymist F510	950 (6.6)	850 (5.9)	600 (4.1)	700 (4.8)	800 (5.5)	2350 (16.2)
Internal mold release	0.5% Mold Wiz 55PV	650 (4.5)	500 (3.5)	150 (1.0)	950 (6.6)	250 (1.7)	3800 (26.2)
Filler	17% 497 Fiberglass	1750 (12.1)	1600 (11.0)	1850 (12.8)	1900 (13.1)	1150 (7.9)	3050 (21.0)
Colorant	0.5% Yellow 55-21007	650 (4.5)	850 (5.9)	450 (3.1)	2950 (20.3)	550 (3.8)	3050 (21.0)

*All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

the bond strengths achieved on PES. The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused a statistically significant decrease in the bondability of PES.

Other Information: PES is extremely sensitive to stress cracking caused by exposure to uncured cyanoacrylate adhesives, so any excess adhesive should be removed from the surface immediately, and cyanoacrylate accelerators should be used whenever possible. PES is compatible with acrylic adhesives, but can be attacked by their activators before the adhesive has cured. Any excess activator should be removed from the surface immediately. PES is incompatible with anaerobic adhesives. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

BASF AG: Ultrason E (features: transparent, amber tint)

Various adhesive systems allow unbreakable bonds to be formed between Ultrason articles or between Ultrason and other materials. Examples are epoxy resins, polyurethanes, phenolic resins, and silicone adhesives. The system is selected to meet the requirements imposed, for example, resistance to heat, moisture, chemicals, etc. Some solvents initiate environmental stress cracking in Ultrason. As a consequence, prior experiment is essential in each case to determine the suitability of an adhesive system. The surfaces to be bonded should be degreased, roughened, or otherwise treated to ensure good adhesion.

The strength of the bonds depends not only on the adhesive but also on the geometry of the joints. Good results are obtained with tongue-and-groove joints. If the overlap is sufficiently long, these joints can transmit more than 60% of the assembly's strength.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

38.1.11 Mechanical Fastening

Solvay Advanced Polymers: Radel A

Self-tapping Screws: Self-tapping screws are suitable for use with Radel A resins. Self-tapping screws provide an economical method for joining plastics because they eliminate the need for molding an internal thread or a separate tapping operation.

Snap-fits: The ductility of Radel engineering resins combined with their strength, make them well suited for snap-fit assembly. The design should not have a maximum strain greater than the permissible strain given in Table 38.3.

Reference: *Radel R, Radel A, Acudel Design Guide*, Supplier design guide (R-50247), Solvay Advanced Polymers, 2004.

BASF AG: Ultrason E (features: transparent, amber tint)

Riveting and Beading: Unbreakable connections between Ultrason parts and other materials, for example, sheet metal, can be easily formed by incorporating rivet shanks in the Ultrason part during the molding process. After the metal part has been pushed onto the shanks, the heads of the rivets are formed by a special ultrasonic tool. A similar principle is adopted in beading: the projecting Ultrason bead is plasticized by ultrasonic means and thus formed to enclose, for example, metal parts.

Detachable Connections: Most suitable for detachable connections are screws and bolts and—with certain restrictions—snap-on connectors. Bolted connections that must withstand heavy loads and those that are frequently dismantled are best formed by housing threaded metal inserts in recesses that have been allowed for them in the Ultrason part during the molding process. These inserts are pressed into the recesses while they are still hot, or—preferably—they are secured by ultrasonic welding.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

38.2 Polysulfone

38.2.1 General

BASF AG: Ultrason S (features: transparent, amber tint)

Unbreakable connections between Ultrason moldings can be formed by the various welding techniques. Adhesives are resorted to for effecting firm bonds between Ultrason and other materials. Other means of forging unbreakable connections are riveting and beading.

Table 38.3. Maximum Permissible Strains for Snap-fit Designs Made from Radel A

Radel Grade	Maximum Permissible Strain
A-200A	6.0
AG-310	3.0
AG-320	1.5
AG-330	1.0

Detachable bonds can be formed by snap-on connectors, screws, and bolts. The threads may be formed during the molding process or may assume the form of metal inserts that are subsequently fixed, for example, by ultrasonic techniques, in recesses provided for them in the moldings.

The conventional welding techniques adopted for thermoplastics are suitable for the various Ultrason products. The only exception is high frequency welding, which is unsuitable for thermoplastics with low dissipation factors. If the Ultrason moldings have picked up moisture, which is usually the case, it is absolutely essential to dry them before welding in order to avoid foaming in the zone of the weld during the melting phase.

The welding technique to be adopted depends on the geometry of the moldings and the stress pattern. Allowance must be made for the fact that molded-in stresses cannot be completely avoided, especially in moldings with very thick walls produced from Ultrason or any other material. Examples of Ultrason welded to other materials are in Table 38.4.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide (B 602 e/10.92), BASF Aktiengesellschaft, 1992.

Amoco Performance Products: Udel (features: transparent, amber tint)

There are many parameters associated with the successful use of the various joining methods for polysulfone. Once the procedure is established for using one of these techniques, the joined parts should be checked periodically to be sure a desirable residual stress level exists.

Table 38.4. Welding Techniques for Joining Ultrason Polysulfone to Other Materials

Material	Suitable Technique
Textiles	Ultrasonic welding
(Pretreated) metal foil	Heated tool welding
Other plastics e.g., poly(butylene terephthalate), acrylonitrile-styrene-acrylate copolymers, and acrylonitrile-butadiene-styrene copolymers	Ultrasonic welding

To optimize the performance of fabricated polysulfone parts, particularly with respect to impact and stress crack resistance, it is recommended that the internal stresses developed during molding, extrusion, forming, joining, etc. be kept to below 1200 psi (8.3 MPa). The relative amount of residual stress in a part can be estimated by allowing the part to contact a series of solvents that vary in their activity towards polysulfone. These are shown with the corresponding approximate residual stress levels in Table 38.5. The approximate level of stress in a polysulfone item is determined as follows. Contact the item with Carbitol solvent (by immersion or swabbing) for one minute and examine the item. If it is crazed, the residual stress level is 1800 psi (12.4 MPa) or greater. If it is not crazed, the residual stress is less than 1800 psi (12.4 MPa). Proceed down the table in similar fashion to find the solvent that induces crazing in one minute. The stress level in the item being tested lies between the stress corresponding to the craze-inducing solvent and the one immediately above it in the table.

It is important to remember that stress can be induced during fabrication, forming, assembly or use and that all such stress can be additive. Thus, to maximize the stress bearing ability of the finished item, stresses arising from other sources should be kept to a minimum.

Reference: *Udel Polysulfone Design Engineering Handbook*, Supplier design guide (F-47178), Amoco Performance Products, Inc., 1988.

38.2.2 Heated Tool Welding

Solvay Advanced Polymers: Udel (features: transparent, amber tint)

The surfaces to be welded are pressed against the hot plate set at 700°F (371°C) for about ten seconds and then joined immediately. Because polysulfone contains a small amount of moisture, it is desirable to dry it for 3 to 6 hours at 250°F (121°C) before attempting to heat weld. A suitable fixture is necessary for fast, proper alignment of the pieces. Metal fixtures heated to about 350°F (177°C) have been used successfully.

Reference: *Udel Polysulfone Design Guide*, Supplier design guide (U-50244), Solvay Advanced Polymers, 2002.

Table 38.5. Approximate Residual Stress in Polysulfone at a Contact Time of 1 minute

Solvent	Approximate Residual Stress, psi (MPa)
Carbitol solvent	1800 (12.4)
Butyl cellosolve	1400 (9.7)
Cellosolve solvent	1200 (8.3)
1,1,1-Trichloroethane	600 (4.1)
Ethyl acetate	<200 (<1.4)
Cellosolve acetate	<200 (<1.4)

BASF AG: Ultrason S (features: transparent, amber tint)

Ultrason necessitates high tool temperatures, for which conventional non-stick layers are unsuitable. In heat contact methods, the tool must be cleaned continuously to remove adhering residues.

Owing to the high temperatures involved, a very brief change-over period, if possible less than one second, is required to prevent the surface of the melt from cooling to a temperature below the melting point. Excellent results have been obtained with the following parameters:

- heated tool temperature 380–550°C (716–1022°F)
- heating-up period 10–90 seconds
- specific joining pressure 2–5 MPa (290–725 psi)

Reference: U*ltrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

38.2.3 Ultrasonic Welding

BASF AG: Ultrason S (features: transparent, amber tint)

Ultrasonic welding is recommended for parts with cross-sectional areas of 200 cm^2 (31 inches^2) or less or for welds of up to 10 cm^2 (1.6 inches^2) area. Larger parts necessitate two or more welding operations, which are performed simultaneously or one after the other. The short time required for welding, viz. two seconds, permits extremely rapid cycling. The geometry of the weld must conform to the requirements for ultrasonic welding. The welding parameters depend on the material and the design of the molding, and particularly good results have been achieved with the following settings:

- frequency 20–40 kHz
- amplitude 20–60 μm

- welding time 0.1–2.0 seconds
- specific welding pressure 1–5 MPa (145–725 psi)

The attainable joint efficiency, that is, the ratio of the strength of the weld to that of the material, lies between 0.3 and 0.6, the actual figure depending on the material and the design of the molding.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

Amoco Performance Products: Udel (features: transparent, amber tint)

Ultrasonics offer a fast, clean, efficient method for bonding polysulfone to itself. Welds can be obtained with a 0.5 second ultrasonic time. This welding cycle is much shorter than that of any other method. A standard cylindrical step horn under 40 psi (0.3 MPa) air cylinder pressure has given good results. A holding fixture is necessary to maintain the parts in proper relationship to each other.

Reference: *Udel Polysulfone Design Engineering Handbook*, Supplier design guide (F-47178), Amoco Performance Products, Inc., 1988.

BASF AG: Ultrason S

Ultrason S moldings can be welded together by ultrasonic techniques, which may also be adopted for countersinking metal parts.

Reference: *Ultrason S Resins*, Supplier technical report (81527 (8106)), BASF, 1988.

38.2.4 Vibration Welding

BASF AG: Ultrason S (features: transparent, amber tint)

The amplitude required for heating the surfaces to be joined depends on the frequency of the machine, for example,

- 100 Hz: 1.0–4.0 mm (0.039–0.157 inches)
- 240 Hz: 0.5–2.0 mm (0.020–0.079 inches)

The welding time should be about 2–10 seconds; and the specific welding pressure, about 1–2 MPa (145–290 psi). Joint efficiencies of 0.4 can be achieved for unreinforced Ultrason resins; and of 0.2, for products containing 20% glass fiber reinforcement.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

38.2.5 Spin Welding

BASF AG: Ultrason S (features: transparent, amber tint)

Spin welding is suitable for Ultrason moldings that have been designed accordingly. The joint efficiencies that can be attained are similar to those achieved in vibration welding.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

38.2.6 Hot Gas Welding

BASF AG: Ultrason S (features: transparent, amber tint)

Hot air welding is suitable for joining large or complicated parts. The air temperature necessary lies between 450 and 500°C (842 and 932°F), and the diameter of the welding rod should correspond to the wall thickness of the molding. This technique is mostly adopted for manual welding and allows V-seams with joint efficiencies as high as 0.7 to be achieved on unreinforced Ultrason panels.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

Amoco Performance Products: Udel (features: transparent, amber tint)

Kamweld Technologies Inc. of Norwood, Massachusetts, has developed a tool for hot gas welding of polysulfone. This tool is recommended to prospective users of polsulfone sheet who are interested in butt welding or fillet welding. Two potential applications are chemical tank linings and hot air ducts. The welding process consists of heating the polysulfone rod and the ends of the sheet simultaneously and joining them immediately after the surfaces have softened. The welding rate is of the order of 20 inches/minute (500 mm/minute) for 4.0 mm (0.156 inch) rod.

Kamweld Model 10-HS-B High-speed Production Welder, with Model KS-1C High-speed tool, is recommended for welding polysulfone, using a 3.2 mm (0.125 inch) or 4.0 mm (0.156 inch) rod. A model KS-2C tool is recommended for 4.8 mm (0.189 inch) rod. Polysulfone welding rods can be obtained from Westlake Plastics, Lenni, PA. For best results, the work and welding rods should be dried just prior to the welding operation.

Reference: *Udel Polysulfone Design Engineering Handbook*, Supplier design guide (F-47178), Amoco Performance Products, Inc., 1988.

38.2.7 Infrared Welding

BASF AG: Ultrason S (features: transparent, amber tint)

Since, in heat contact methods, the tool must continuously be cleaned to remove adhering residues, preference should be given to IR welding. The spacing between the parts to be welded and the heated tool should be about 0.2–0.6 mm (0.008–0.024 inches).

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide (B 602 e/10.92), BASF Aktiengesellschaft, 1992.

38.2.8 Induction Welding

Amoco Performance Products: Udel (features: transparent, amber tint)

Strong bonds can be obtained by magnetic induction heating of an interlayer containing ferromagnetic particles. Systems are supplied by Emabond Solutions.

Reference: *Udel Polysulfone Design Engineering Handbook*, Supplier design guide (F-47178), Amoco Performance Products, Inc., 1988.

38.2.9 Solvent Welding

BASF AG: Ultrason S (features: transparent, amber tint)

Ultrason can also be bonded with solvents such as N-methyl-2-pyrrolidone (NMP), N,N-dimethylformamide and dichloromethane. Allowance must be made for the fact that these solvents may give rise to environmental stress cracking in parts that are subjected to mechanical stress. Their viscosity can be raised by adding 3–15% of Ultrason. In any event, the bonds must be allowed sufficient time to dry, that is, for complete removal of the solvent.

The strength of the bonds depends not only on the adhesive but also on the geometry of the joints. Good results are obtained with tongue-and-groove joints. If the overlap is sufficiently long, these joints can transmit more than 60% of the assembly's strength.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

Amoco Performance Products: Udel (features: transparent, amber tint)

For solvent bonding of polysulfone, a 5% solution of resin in methylene chloride can be used. Also available is a gelled methylene chloride cement, designated (Zip Strip), made by Star Bronze Co. This cement is formulated to provide several minutes of open time after application.

The best solvent bonds are achieved by applying the minimum solvent needed to wet the surfaces to be joined. A convenient way of accomplishing this when edge joining is to use a capillary medicine dropper to apply a thin film of solvent along each edge. The two pieces should then be assembled in a jig and placed in a cold press for five minutes at 500 psi (3.4 MPa). At this point the joint should be clear and bubble-free. The presence of bubbles indicates an excess of solvent and/or insufficient pressure. Squeeze-out indicates too high pressure or excess solvent.

To use a solvent for bonding metal to polysulfone it is first necessary to adhere a layer of 3–5 mil (0.076–0.127 mm) polysulfone film to the metal. In the case of aluminum, the film can be bonded directly to the metal at 700°F (371°C) using a set of nip rolls. With steel, priming is necessary and the temperature should be 600°F (316°C). The metal can then be solvent fused to polysulfone as previously described.

The strength of this joint will improve over a period of several weeks as the residual solvent evaporates. Properly prepared joints using either heat or solvent fusion techniques have surpassed the strength of the polysulfone adherends. Solvent bonding is not recommended where bond areas will come in contact with even weak environmental stress cracking agents. Solvent bonding to other plastics is possible using a mutual solvent and the same procedure described above.

Best results will be obtained when mating parts are flush and in intimate contact with each other. This means that parts should be machined square and surfaces sanded smooth.

Reference: *Udel Polysulfone Design Engineering Handbook*, Supplier design guide (F-47178), Amoco Performance Products, Inc., 1988.

BASF AG: Ultrason S

Ultrason S moldings can be bonded together with solvents such as *N*-methyl-2-pyrrolidone (NMP) and dichloromethane or their blends. Allowance must be made for the fact that these solvents may give rise to environmental stress cracking in parts subjected to load.

The solvents can be made more viscous by adding 3–15% of polysulfone. In any event, sufficient time must be allowed for the solvent to evaporate.

Reference: *Ultrason S Resins*, Supplier technical report (81527 (8106)), BASF, 1988.

38.2.10 Adhesive Bonding

Solvay Advanced Polymers: Udel

A study was conducted to determine the bond strength of polysulfone and the adhesives best suited to it. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad.

While the bond strengths in Table 38.6 give a good indication of the typical bond strengths that can be achieved they also face several limitations. For example, a consideration that must be kept in mind when using this data to select a suitable adhesive is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Loctite 3105, a light curing acrylic adhesive, consistently achieved the highest bond strengths on polysulfone. Prism 401, a surface insensitive cyanoacrylate adhesive achieved the second highest bond strengths. Prism 401, when used in conjunction with Prism Primer 770, achieved the lowest bond strengths.

Surface Treatments: The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused a statistically significant decrease in the bondability of polysulfone.

Other Information: Polysulfone is extremely sensitive to stress cracking caused by exposure to uncured cyanoacrylate adhesives, so any excess adhesive should be removed from the surface immediately, and cyanoacrylate accelerators should be used whenever possible. Polysulfone is compatible with acrylic adhesives, but can be attacked by their activators before the adhesive has cured. Any excess activator should be removed from the surface immediately. Polysulfone is incompatible with anaerobic adhesives. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

Table 38.6. Shear Strengths of Udel P-1700 Polysulfone to Polysulfone Adhesive Bonds Made Using Adhesives Available from Loctite Corporation*

	Loctite Adhesive					
Material Composition	**Black Max 380** (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	650 (4.5)	1600 (11.0)	150 (1.0)	700 (4.8)	900 (6.2)	3050 (21.0)

*All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

BASF AG: Ultrason S (features: transparent, amber tint)

Various adhesive systems allow unbreakable bonds to be formed between Ultrason articles or between Ultrason and other materials. Examples are epoxy resins, polyurethanes, phenolic resins, and silicone adhesives. The system is selected to meet the requirements imposed, for example, resistance to heat, moisture, chemicals, etc. Some solvents initiate environmental stress cracking in Ultrason. As a consequence, prior experimentation is essential in each case to determine the suitability of an adhesive system. The surfaces to be bonded should be degreased, roughened, or otherwise treated to ensure good adhesion.

The strength of the bonds depends not only on the adhesive but also on the geometry of the joints. Good results are obtained with tongue-and-groove joints. If the overlap is sufficiently long, these joints can transmit more than 60% of the assembly's strength.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

Amoco Performance Products: Udel (features: transparent, amber tint)

A number of adhesives have been found suitable for joining polysulfone to itself or to other materials. Some of these are recommended only for relatively low temperature applications. Others give bonds that retain their integrity at temperatures approaching the continuous service temperature of polysulfone itself.

Reference: *Udel Polysulfone Design Engineering Handbook*, Supplier design guide (F-47178), Amoco Performance Products, Inc., 1988.

38.2.11 Mechanical Fastening

BASF AG: Ultrason S (features: transparent, amber tint)

Riveting and Beading: Unbreakable connections between Ultrason parts and other materials, for example, sheet metal, can be easily formed by incorporating rivet shanks in the Ultrason part during the molding process. After the metal part has been pushed onto the shanks, the heads of the rivets are formed by a special ultrasonic tool. A similar principle is adopted in beading: the projecting Ultrason bead is plasticized by ultrasonic means and thus formed to enclose, for example, metal parts.

Detachable Connections: Most suitable for detachable connections are screws and bolts and—with certain restrictions—snap-on connectors. Bolted connections that must withstand heavy loads and those that are frequently dismantled are best formed by housing threaded metal inserts in recesses that have been allowed for them in the Ultrason part during the molding process. These inserts are pressed into the recesses while they are still hot, or—preferably—they are secured by ultrasonic welding.

Reference: *Ultrason E, Ultrason S Product Line, Properties, Processing*, Supplier design guide, BASF Aktiengesellschaft.

Amoco Performance Products: Udel (features: transparent, amber tint)

Press-fit Assemblies: Because of the inherent dimensional stability and creep resistance of polysulfone, press fitting can be used to advantage as a technique of assembly or installation of accessories. Generally, the amount of interference will be less than that required for other thermoplastics and holding power will be retained to a higher degree. Recommended diametral interference values for a steel shaft in a polysulfone hub have been determined (Fig. 38.1). These values apply to operating environments up to 200°F (93°C) in air and have been derived from standard design formulas. A hoop stress of 2000 psi (13.8 MPa) has been used in the calculations and allowance has been made for creep.

Tapping and Self-tapping Screws: Standard steel working taps work well with polysulfone. Lubricants or cutting oils are not required, although a light lubricating oil may be used to reduce tap wear. A two or three flute tap may be used at speeds of 35–75 ft/minute (180–380 mm/s) with good results.

Self-tapping screws, such as Type BF, have been tested in polysulfone and found to give satisfactory results.

Molded-in Threads: The first three classes of the Unified Thread Standard with a rounded root should be used. Threads should not run to the very end of a threaded section. A clear area of at least 0.031 inches (0.79 mm) should be provided (Fig. 38.2). Pipe threads are not recommended because they induce a severe wedging action.

Threaded Mechanical Inserts: Threaded metal inserts provide a convenient means of fastening molded polysulfone articles to other components. In general, inserts installed after molding are preferred over molded-in inserts. They are usually less costly and the high stress accumulation due to differential cooling of

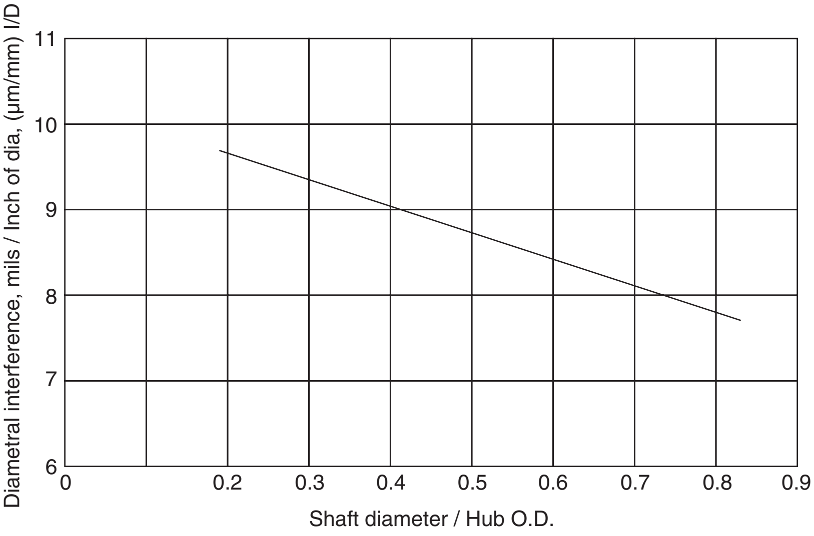


Figure 38.1. Recommended diametral interference for press fits using a polysulfone hub and a steel shaft.

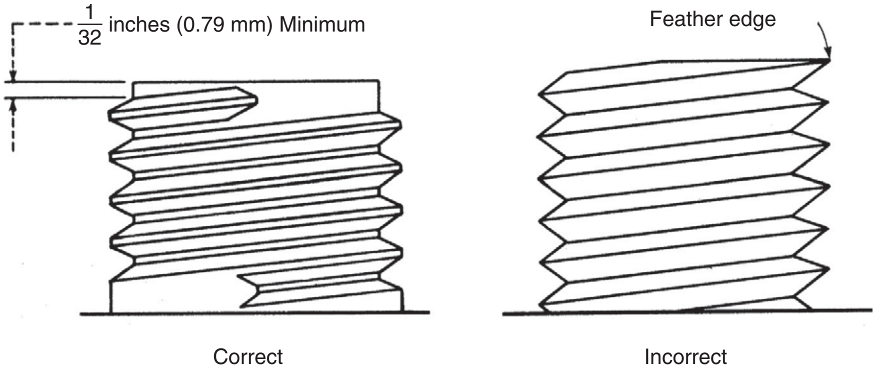


Figure 38.2. Molded-in thread design for polysulfone.

Table 38.7. Post-molding Threaded Inserts for Use with Polysulfone

Trade name	Type	Internal Thread	Manufacturer's Part Code	Pilot Hole and Drill Size	Counter Bore
"Tap-Lok"	Thread cutting	6–32	C-Series, coarse external thread	0.1935" (#10) (4.91 mm)	7/32" × 1/16" (5.56 mm × 1.59 mm) deep
		10–32	C-series, coarse external thread	0.226" (H) (5.74 mm)	19/64" × 1/16" (7.54 mm × 1.59 mm) deep
"Banc-Lok"	Expansion	6–32	N-series	0.187" (3/16") (4.75 mm)	–
		10–32	N-series	0.246" (D) (6.25 mm)	–
"Dodge"	Expansion	6–32	–	0.187" (3/16") (4.75 mm)	–
		10–32	–	0.246" (D) (6.25 mm)	–

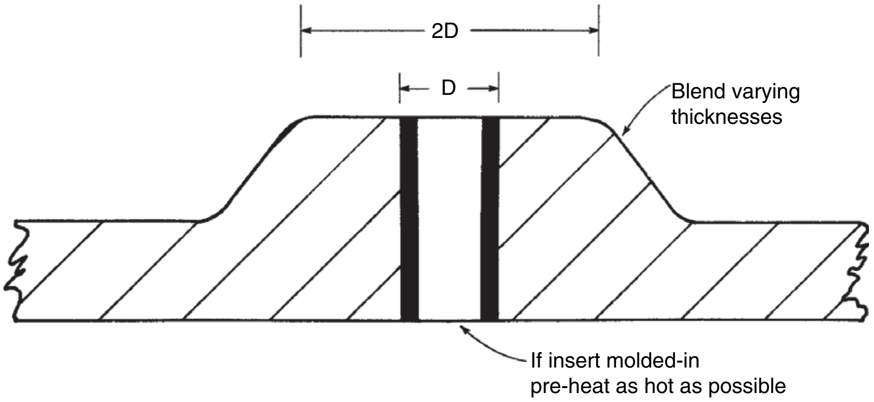


Figure 38.3. Boss design for polysulfone.

the resin and a molded-in insert is avoided. A variety of inserts can be used with polysulfone (Table 38.7). The standard rule that wall thickness around the insert should be at least one-half the insert's major diameter should be followed. It is also possible to install metal inserts with ultrasonic devices. This will usually result in excellent resistance to pull out or stripping combined with a minimum of residual stress. If molded-in inserts are desired, pre-heat the insert as hot as possible prior to molding. This will minimize internal stress on the polysulfone boss.

Bosses: Locate bosses at the junction of two surfaces, such as a corner, if possible. Boss outer diameter should be twice the diameter of the hole. Boss height should not exceed twice the boss outer diameter (Fig. 38.3).

Reference: *Udel Polysulfone Design Engineering Handbook*, Supplier design guide (F-47178), Amoco Performance Products, Inc., 1988.

38.3 Polyphenylsulfone

38.3.1 Mechanical Fastening

Solvay Advanced Polymers: Radel R

Self-tapping Screws: Self-tapping screws are suitable for use with Radel R resins. Self-tapping screws provide an economical method for joining plastics because they eliminate the need for molding an internal thread or a separate tapping operation.

Snap-fits: The ductility of Radel engineering resins combined with their strength, make them well suited for snap-fit assembly. The design should not have a maximum strain greater than the permissible strain which, for grades 5000, 5100 and 5200 is 6.7%.

Reference: *Radel R, Radel A, Acudel Design Guide*, Supplier design guide (R-50247), Solvay Advanced Polymers, 2004.

39 Vinyls

39.1 Polyvinyl Chloride

39.1.1 General

Georgia Gulf: PVC

Parts molded from Georgia Gulf rigid vinyl compounds can be fastened together in a variety of ways. Whether the methods are through mechanical or chemical means, consideration early in the design stages will facilitate a proper and economic assembly to meet intended requirements. When considering the fastening options available with rigid vinyl, a designer must decide whether the parts will be assembled with or without fasteners (Table 39.1).

The use of ultrasonic, spin, and vibration welding works very well with rigid vinyl. Heat staking is also an acceptable method of joining parts.

Reference: *Georgia Gulf Vinyl*, Supplier technical report, Georgia Gulf, 1991.

39.1.2 Heated Tool Welding

Geon: Geon (form: injection-molded plaque)

PVC has been shown to weld well using heated tool welding. The maximum achievable weld strength depends on the material grade. Relative weld strengths of about 85% and 97%, with corresponding failure strains of about 2.5% and 3.3%, have been demonstrated in welds of Geon 87416 and Geon 85885, respectively.

Reference: Stokes VK: Hot-tool and vibration welding of poly(vinyl chloride). *Journal of Vinyl & Additive Technology*, 6(3), p. 158, September 2000.

Table 39.1. Available Options for Joining Rigid PVC Parts

Fasteners	Without Fasteners
Thread-cutting screws	Solvent bonding
Thread-forming screws	Adhesive bonding
Clips	Snap fits
Machine screws	Welding techniques: ultrasonic, spin, vibration, heat staking

Huls AG: Vestolit BAU (applications: windows; chemical type: graft polymer; form: profile extrusion)

The welding of mitre-cut profiles into window frames is carried out on specially-designed heat welding machines. Essential requirements for optimum welding are high dimensional accuracy of the profiles and mitre-cut surfaces without chips or fractures. The PVC used must meet the requirements for good weldability. From the raw-material side, the following factors should be mentioned which can influence weldability:

- Method of manufacturing the PVC.
- Modification of the PVC (modifier).
- Formulation of the PVC (lubricant and chalk content).

The additives used in the Vestolit BAU compounds are selected carefully with a view to not adversely affect the weldability. The weldability is tested in the tensile test to DIN 53455 with welded and nonwelded specimens. The welding factor (tensile strength (welded)/tensile strength (no weld)) is derived from the tensile strengths at break. With Vestolit BAU it is for practical purposes always about 1.0.

The removal of the weld "flux" is usually carried out mechanically on automatic machines. In contrast to non-modified rigid PVC, profiles made from Vestolit BAU permit high production rates of the routers, necessary to ensure minimum operation times at this station. Experience in the early development stages demonstrated that at these high cutting speeds, profiles with a notched impact strength of 20 kJ/m^2 or less showed "chatter marks" when withdrawn, or the outer corner edges of the frame chipped during routing of the weld flux.

Reference: *Vestolit BAU for World-wide Windows*, Supplier technical report (1083e/May 1987/bu), Huls AG, 1987.

39.1.3 Ultrasonic Welding

PVC (features: 5.8 mm (0.228 inches) thick)

Ultrasonic bonding of PVC sheet or fiber is difficult to predict due to the broad range of additives used in its manufacture. Plasticizers are often added to rigid PVC to impart flexibility. As the content of plasticizer increases, the ability to ultrasonically bond PVC decreases.

Reference: *Ultrasonic Sealing and Slitting of Synthetic Fabrics*, Supplier technical report, Sonic & Materials, Inc.

39.1.4 Vibration Welding

Geon: Geon (form: injection-molded plaque)

PVC has been shown to weld well using vibration welding. The maximum achievable weld strength depends on the material grade. Relative weld strengths of about 85% and 97%, with corresponding failure strains of about 2.5% and 3.3%, have been demonstrated in welds of Geon 87416 and Geon 85885, respectively.

Reference: Stokes VK: Hot-tool and vibration welding of poly(vinyl chloride). *Journal of Vinyl & Additive Technology*, 6(3), p. 158, September 2000.

39.1.5 Radio Frequency Welding

PVC (features: transparent)

Difficulties were encountered in regulating RF welding conditions for rigid PVC to get acceptable, aesthetically pleasing welds. Rigid PVC did not produce sound bonds to itself. Depending on welding parameters, the samples either did not melt, or melted completely through before a good bond could be formed. Nevertheless, good bonds were achieved with rigid/clear flexible PVC, rigid/radiopaque-filled flexible PVC, and rigid/polyurethane combinations (Table 39.2).

As with flexible PVC, heat ageing had no noticeable effects, except in the case of the rigid PVC/polyurethane combination, which increased significantly in weld strength after ageing. With rigid PVC, samples purposely cut through during welding produced superior welds to samples not cut through. This was probably due to the longer contact time (the time in which the pressure and RF frequency were applied

Table 39.2. Radio Frequency Weld Strength of Rigid PVC Between Itself and Other Materials*

Material	Joining Material	RF Welded Without Cutting through Samples	Samples Purposely Cut Through during RF Welding		Change in Weld Strength after Exposure to 5–5.5 Mrads of Gamma Radiation
			No Aging	Aged 48 hours at 60°C (140°F)	
Clear rigid PVC 80D	TPE alloy	No bond	No bond		
Clear rigid PVC 80D	Styrenic TPE	No bond	No bond		
Clear rigid PVC 80D	Aromatic polyester polyurethane	Fair (6–15% potential)	Excellent (31–50% potential)	Superior (>50% potential)	
Clear rigid PVC 80D	Filled radiopaque PVC 75A	Fair (6–15% potential)	Superior (>50% potential)	Excellent (31–50% potential)	
Clear rigid PVC 80D	Clear rigid PVC 80D	Weak (<5% potential)	Fair (6–15% potential)	Fair (6–15% potential)	–5% potential
Clear rigid PVC 80D	Clear flexible PVC 80A	Excellent (31–50% potential)	Good (16–30% potential)	Superior (>50% potential)	
Clear rigid PVC 80D	Clear flexible PVC 65A	Fair (6–15% potential)	Excellent (31–50% potential)	Excellent (31–50% potential)	

*The breaking strength per unit cross-sectional area of each weld was calculated, and then divided by the tensile strength of the weaker material. This number (multiplied by 100) gave the weld strength expressed as a percentage of the highest possible value or “potential”.

to the sample) used in the purposely cut through samples.

Reference: Leighton J, Brantley T, Szabo E: RF welding of PVC and other thermoplastic compounds. ANTEC 1992, Conference proceedings, Society of Plastics Engineers, Detroit, May 1992.

39.1.6 Hot Gas Welding

PVC-U (form: sheet)

The following welding conditions are recommended for PVC-U: temperature of 320–370ºC (608–698°F), force (for a 4 mm (0.157 inch) diameter welding rod) of 15–25 N (3.4–5.6 lbf) and a gas flow of 40–60 l/minute.

Reference: Gibbesch B: Thermoplastic inliner for dual laminate constructions. Welding Beyond Metal: AWS/DVS conference on Plastics Welding, New Orleans, March 2002.

39.1.7 Solvent Welding

PVC (form: pipe)

A study was conducted on solvent cement joints in uPVC pipes to determine their mechanical strength and the characteristics of the bond between the pipe and the spigot. Spigots and sockets were joined with Plaskem Type-P solvent cement (manufactured by Plaskem Adhesives and Sealants).

The strength of solvent cement joints depends on the time that is allowed for the cure of the joint. Joints cured for 60 days reached a shear strength of 9 MPa (1305 psi). The interfaces were very distinct and no interaction between the polymer and solvent cement could be observed.

Reference: Tjandraatmadja GF, Burn LS: A study of the solvent cement bond for PVC and ABS pipe joints. Plastics Pipes XI, Conference proceedings, Munich, Germany, September 2001.

Georgia Gulf: PVC

Solvent welding is a very effective method for joining several rigid vinyl parts or other thermoplastics soluble in the same solvent. The procedure involves treating the surface to be welded with a small amount of solvent to etch the contact area. A fixture is recommended to hold the mated parts together until the solvent has evaporated, and the parts joined. It is important that the mating surfaces fit well so that pressure can be evenly distributed over the entire surface area to be welded.

A 5–20% solution of PVC resin in methylene chloride and THF provides an effective solvent welding system. Proper ventilation of the work area and adherence to plant safety should always be followed when working with solvents. The amount of cement should be kept to a minimum and applied only to clean surfaces to insure high-quality aesthetics and proper welding.

The following solvent welding procedure should be used:

(1) Clean the parts to be welded.
(2) Apply solvent to one side only.
(3) Clamp the two parts together (minimum 60–90 seconds).
(4) If the part is to be used in a room temperature environment, dry at room temperature for 24 hours.

Performance of parts mated by a solvent can be greatly enhanced by proper joint design of the mating surfaces. A strong surface bond is directly related to the size of the surface mating area of the parts. Welded joints under compression perform optimally; therefore, compression should be utilized whenever possible in joint design. Under conditions of tension, lap joints perform with more reliability due to increased surface contact area in lap joint configurations.

Reference: *Georgia Gulf Vinyl*, Supplier technical report, Georgia Gulf, 1991.

Dexter Composites: Alpha 2212 (features: transparent)

In tests conducted to evaluate the solvent bondability/compatibility of plasticized PVC tubing to rigid, transparent thermoplastics, as might have been predicted, PVC bonds quite well to PVC. All solvents but acetone allowed for easy assembly. The 1,2-dichloroethane and straight methylene chloride did not provide acceptable bond strengths, but all of the other cocktails did yield acceptable bonds. No initial crazing was observed for any of the solvents. The instance of a rigid PVC substrate is one case where straight cyclohexanone will provide results that are as good as those for any of the blends.

Reference: Haskell A: Bondability/compatibility of plasticized PVC to rigid, transparent thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

39.1.8 Adhesive Bonding

Occidental: Oxychem 160

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 39.3 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example,

Table 39.3. Shear Strengths of Oxychem 160 PVC to PVC Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[b]

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super bonder 414** (Instant Adhesive General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin	3 rms	>1600[a] (>11.0)[a]	>3650[a] (>25.2)[a]	>2850[a] (>19.7)[a]	>2900[a] (>20.0)[a]	>2650[a] (>18.3)[a]	>2550[a] (>17.6)[a]
Roughened	27 rms	>1600[a] (>11.0)[a]	>1850[a] (>12.8)[a]	>1400[a] (>9.7)[a]	>2900[a] (>20.0)[a]	>1550[a] (>10.7)[a]	>2550[a] (>17.6)[a]
UV stabilizer	1% UV-531	>1600[a] (>11.0)[a]	>2800[a] (>19.3)[a]	>1400[a] (>9.7)[a]	>2900[a] (>20.0)[a]	>1850[a] (>12.8)[a]	>2550[a] (>17.6)[a]
Impact modifier	7% Paraloid BTA753	>1100[a] (>7.6)[a]	>4300[a] (>29.7)[a]	>3650[a] (>25.2)[a]	>2900[a] (>20.0)[a]	1050 (7.2)	>3000[a] (>20.7)[a]
Flame retardant	0.3% Antimony Oxide	>1600[a] (>11.0)[a]	>3050[a] (>21.0)[a]	>2850[a] (>19.7)[a]	>2900[a] (>20.0)[a]	>2050[a] (>14.1)[a]	>2550[a] (>17.6)[a]
Smoke suppressant	0.3% Ammonium Octamolybdate	1250 (8.6)	>3650[a] (>25.2)[a]	>2850[a] (>19.7)[a]	>2900[a] (>20.0)[a]	>1800[a] (>12.4)[a]	>2550[a] (>17.6)[a]
Lubricant	1% Calcium Stearate 24-46	>1600[a] (>11.0)[a]	>3650[a] (>25.2)[a]	>2850[a] (>19.7)[a]	>2900[a] (>20.0)[a]	>1900[a] (>13.1)[a]	>2550[a] (>17.6)[a]
Filler	9% OmyaCarb F	>1600[a] (>11.0)[a]	>4250[a] (>29.3)[a]	>1750[a] (>12.1)[a]	>4400[a] (>30.3)[a]	>2650[a] (>18.3)[a]	>3150[a] (>21.7)[a]
Plasticizer	5% Drapex 6.8	>1600[a] (>11.0)[a]	>2250[a] (>15.5)[a]	>1550[a] (>10.7)[a]	>2900[a] (>20.0)[a]	>1500[a] (>10.3)[a]	>2550[a] (>17.6)[a]
Colorant	0.5% FD&C Blue #1	>1600[a] (>11.0)[a]	>3650[a] (>25.2)[a]	>2850[a] (>19.7)[a]	>2900[a] (>20.0)[a]	>1050[a] (>7.2)[a]	>2550[a] (>17.6)[a]
Antistatic	1.5% Markstat AL48	>1600[a] (>11.0)[a]	>3650[a] (>25.2)[a]	>1200[a] (>8.3)[a]	>2900[a] (>20.0)[a]	>900[a] (>6.2)[a]	>2550[a] (>17.6)[a]

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 39.3 so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Black Max 380, Prism 401, and Super Bonder 414 instant adhesives, Depend 330, a two-part no-mix adhesive, and Flashcure 4305 and 3105 light-curing adhesives, all created bonds that were stronger than the rigid PVC substrate for most of the formulations tested. Excellent bond strength was also obtained by Speedbonder H3000 structural adhesive, Loctite 3030 adhesive, Hysol E-90FL and E-30CL epoxy adhesives, Hysol 3631 hot melt adhesive and Fixmaster rapid rubber repair.

Surface Treatments: Surface roughening and/or the use of Prism Primer 770 or 7701 resulted in either no statistically significant effect, or in the rigid PVC failing at a statistically significant lower bond strength than the untreated PVC.

Other Information: PVC can be stress cracked by uncured cyanoacrylate adhesives, so any excess adhesive should be removed from the surface immediately. PVC is compatible with acrylic adhesives but can be attacked by their activators before the adhesive has cured. Any excess activator should be removed from the surface of the PVC immediately. PVC is incompatible with anaerobic adhesives. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

PVC

PVC can be bonded as received using cyanoacrylate adhesive.

Reference: *The Engineers Guide to Adhesives*, Supplier design guide, Permabond Engineering Adhesives.

Georgia Gulf: PVC

Rigid vinyl parts can be bonded to other materials such as metal, glass, other plastics, and wood. There are a variety of adhesives that will work well with rigid vinyl, such as epoxies, urethanes, contact glues, and two-part adhesive systems.

The following bonding procedure should be used:

(1) Clean parts to be bonded.
(2) Apply adhesive to one side only.
(3) Clamp the two parts together (minimum 60–90 seconds).
(4) If the part is to be used in a room temperature environment, dry at room temperature for 24 hours.

Performance of parts mated by a contact adhesive can be greatly enhanced by proper joint design of the mating surfaces. A strong surface bond is directly related to the size of the surface mating area of the parts.

Bonded joints under compression perform optimally; therefore, compression should be utilized whenever possible in joint design. Under conditions of tension, lap joints perform with more reliability due to increased surface contact area in lap joint configurations.

Reference: *Georgia Gulf Vinyl*, Supplier technical report, Georgia Gulf, 1991.

39.1.9 Mechanical Fastening

Georgia Gulf: PVC

Self-threading screws are a popular and economical way to assemble rigid vinyl parts. The two basic options for screw fasteners are thread-forming and thread-cutting screws. Thread-forming screws are not recommended for rigid vinyl parts as they induce high stress levels in the part. This screw displaces material as it is installed in the receiving hole and creates high stress levels on the boss. Where higher back out torques are required, thread-forming screws may be necessary.

Thread-cutting screws such as the Hi-Lo, Type F, Type 25, and Type 23 are preferred. These screws actually remove material as they are installed, thus avoiding high stress build-up. If the part will be assembled and disassembled several times, Type 23 and Type 25 screws should not be used. The recutting of threads will not offer the required assembly strength and, therefore, a standard machine screw with a brass insert should be used for these applications.

Some general design considerations for mechanical fasteners are as follows:

- The outside diameter of the boss should be equal to 2.25 times the diameter of the cored hole.
- The diameter of the hole [boss] should be equal to the pitch diameter of the screw.
- The thread engagement should be a minimum of twice the screw diameter. A slight increase in the thread engagement will offer a significant increase in pull-out strength.
- Repeated use of the same boss should be avoided.
- Minimum torque should be used to keep stress levels within acceptable limits for rigid vinyl.

Reference: *Georgia Gulf Vinyl*, Supplier technical report, Georgia Gulf, 1991.

39.2 Chlorinated Polyvinyl Chloride

39.2.1 General

Noveon: Corzan (form: pipe)

Corzan piping can be installed using a number of joining techniques. Solvent welding, flanging, and threading are the most common methods. Back welding using hot gas welding is also possible. Less common joining methods for Corzan piping and fittings include butt fusion welding.

Reference: *Corzan Industrial Systems Data*, Supplier installation guide, Noveon Inc.

39.2.2 Hot Gas Welding

PVC-C (form: sheet)

The following welding conditions are recommended for PVC-C: temperature of 350–370ºC (662–698°F), force (for a 4 mm (0.157 inch) diameter welding rod) of 20–25 N (4.5–5.6 lbf) and a gas flow of 40–60 liters/minute.

Reference: Gibbesch B: Thermoplastic inliner for dual laminate constructions. Welding Beyond Metal: AWS/DVS conference on Plastics Welding, New Orleans, March 2002.

Noveon: Corzan (form: pipe)

For hot gas welding by feeding the rod manually, the welding temperature should be approximately 550–600°F (288–316°C). Only welding rod made from Corzan CPVC should be used for welding Corzan CPVC joints.

Reference: *Corzan Industrial Systems Data*, Supplier installation guide, Noveon Inc.

39.2.3 Solvent Welding

Noveon: Corzan (form: pipe)

When solvent welding Corzan pipe and fittings, use a primer conforming to ASTM F656 and a cPVC solvent conforming to ASTM F493.

After a joint is assembled using primer and solvent cement, it should not be disturbed for a period of time to allow for the proper ‘set’ of the newly prepared joint. These times must be adjusted for weather conditions (relative humidity). In damp or humid weather, allow for 50% more set time. Recommended times are given in Table 39.4.

A joint that has cured sufficiently to pressure test may not exhibit its full joint strength. Solvent cement cure times are a function of pipe size, temperature, and relative humidity. Curing times are shorter for drier environments, smaller sizes, and higher temperatures. Moisture can slow the cure time and reduce joint strength. Table 39.5 gives the minimum cure times after the last joint has been made before pressure testing can begin. The presence of hot water extends the cure time required for pressure testing.

Reference: *Corzan Industrial Systems Data*, Supplier installation guide, Noveon Inc.

Table 39.4. Average Initial Set Times for 2.5–6 inch Diameter Corzan Pipe

	Ambient Temperature during Set Period		
	60–100°F (16–38°C)	40–60°F (4–16°C)	0–40°F (-18–4°C)
Set time	30 minutes	2 hours	12 hrs

Table 39.5. Minimum Cure Prior to Pressure Testing at 100 psi (0.69 MPa) for 2½–6 inch (63–152 mm) Diameter Pipe Using Primer and Solvent Cement

	Ambient Temperature during Set Period		
	60–100°F (16–38°C)	40–60°F (4–16°C)	0–40°F (-18–4°C)
Cure time	1½ hours	4 hours	72 hours

39.3 Polyvinylidene Chloride

39.3.1 Ultrasonic Welding

Dow Chemical: Saranex (form: film)

Saranex film may be ultrasonically sealed using similar techniques to those employed with polyethylene film. Ultrasonic sealing is suggested for long continuous seals and results in clean, strong seals at speeds as fast as 120 feet per minute (36 m/minute).

Reference: *Sealing Saranex Films*, Supplier technical report (500-01247-0202X SMG), Dow Chemical Co., 2002.

39.3.2 Hot Gas Welding

Dow Chemical: Saranex (form: film)

Hot air sealing is recommended for continuous sealing of Saranex film on high speed machinery. Extremely strong seals are made at commerical rates of over 100 feet per minute (30 m/minute).

Reference: *Sealing Saranex Films*, Supplier technical report (500-01247-0202X SMG), Dow Chemical Co., 2002.

39.3.3 Heat Sealing

Dow Chemical: Saranex (form: film)

Equipment used to heat seal polyethylene may be efficiently used to seal Saranex film to itself. Such seals are often as strong as the film itself.

Impulse sealing of Saranex film is commercially accomplished at recommended short heat dwell times of 0.25–0.50 seconds, pressures of 10–40 psi (0.069–0.276 MPa), and cooling times of 0–0.25 seconds. Excessive heat and/or over-heating during sealer malfunctions can cause Saranex film to degrade. The products of thermal degradation can be noxious and toxic (under conditions of high concentration or prolonged exposure) to workers.

Reference: *Sealing Saranex Films*, Supplier technical report (500-01247-0202X SMG), Dow Chemical Co., 2002.

40 Plastic Alloys

40.1 ABS/PVC Alloy

40.1.1 Solvent Welding

A. Schulman: Polyman

When employing adhesive and solvent welding techniques, the use of solvent systems such as tetrahydrofuran and methyl ethyl ketone (MEK), or cyclohexanone and perchloroethylene will take advantage of the vinyl- and ABS- like chemical properties of most Polyman alloys.

Reference: *Polyman*, Supplier design guide, A. Schulman Inc.

40.1.2 Mechanical Fastening

A. Schulman: Polyman

Polyman alloys provide close molding tolerances and retain their as-molded properties over a range of temperature and environmental conditions and time. A wide range of fastening and assembly techniques can be successfully used with confidence.

For mechanical assembly, Polyman alloy characteristics are especially suited to the use of induction heat insertion of metal inserts or Dodge expansion inserts. The use of finger engagement snap-in fits frequently found in automotive connectors are also excellent design solutions for a Polyman alloy part assembly. Molded-in inserts, while the strongest fastening technique, involve longer cycle times and should be reserved for situations where part loading demands superior joint integrity. When self-tapping screw joining is used, screws should be of the type normally used for ABS plastics with deeper threads than those designed for polycarbonate plastic. Ultrasonic insertions are other practical and frequently used assembly solutions to which Polyman alloys are well suited.

Reference: *Polyman*, Supplier design guide, A. Schulman Inc.

40.2 Acrylic/PVC Alloy

40.2.1 Heated Tool Welding

Kleerdex: Kydex (form: sheet)

Kydex can be welded to itself and to cast or extruded Plexiglas by hot blade welding. Good joint strength can be achieved using a nichrome heating blade equipped with a thermocouple and a temperature indicator. Blade temperature should be at least 620°F (327°C) with dwell times from 3 to 10 seconds.

Reference: *Physical Properties Kydex 100 Acrylic PVC Alloy Sheet*, Supplier technical report (KC-89-03), Kleerdex Company, 1989.

40.2.2 Ultrasonic Welding

Kleerdex: Kydex (form: sheet)

Ultrasonic spot welding is a practical assembly method for joining Kydex sheet parts in all thicknesses. Properly made joints, with the welder tip, known as the horn, applied to the rear surface, will produce strong joints with the front or finished surface, free of any blemishes.

As a guide to determining the best conditions for a specific application, the test results given in Table 40.1 may be used.

Reference: *Ultrasonic Welding KYDEX Thermoplastic Sheet*, Supplier technical brief (TB-112), Kleerdex Company, 2007.

40.2.3 Hot Gas Welding

Kleerdex: Kydex (form: sheet)

Kydex sheet can be joined to itself and to other materials by hot gas welding. For best results, sheet thickness should be within a range of 2.00–3.18 mm (0.08–0.125 inches). While welding, apply a continuous force of approximately 3 lbf (13 N) on the welding rod. For hand welding, a welding speed of 6–8 inches/minute

Table 40.1. Ultrasonic Welding Parameters for Kydex Sheet

Kydex Sheet Thickness	Weld Time	Pressure
3.18 mm (0.125 in.)	2.0 s	551 kPa (80 psi)
2.00 mm (0.080 in.)	0.7 s	345 kPa (50 psi)

(150–200 mm/minute) should be kept; for speed welding, speeds up to 40 inches/minute (1000 mm/minute) may be obtained.

Reference: *Hot Gas Welding KYDEX Thermoplastic Sheet*, Supplier technical brief (TB-113), Kleerdex Company, 2007.

Kleerdex: Kydex (form: sheet)

High strength joints in Kydex can be obtained through hot gas welding. Kydex or ordinary PVC rod stock fed through a hand-held welding gun is heated and then beaded in its soft state into the joint between two Kydex sheets. The Kydex edges to be joined should be beveled to accommodate the bead which produces the weld. Considerable skill is required in hot gas welding to obtain consistently high strength joints.

Reference: *Physical Properties Kydex 100 Acrylic PVC Alloy Sheet*, Supplier technical report (KC-89-03), Kleerdex Company, 1989.

40.2.4 Solvent Welding

Kleerdex: Kydex (form: sheet)

Due to its excellent chemical resistance, Kydex thermoplastic sheet can be more difficult to cement than other plastics.

The best joints can be obtained using viscous solvent cement consisting of about 10% Kydex sheet shavings or sawdust dissolved in a 50/50 mixture of tetrahydrofuran (THF) and MEK. The shavings should be dissolved in the straight THF first, before adding the appropriate amount of MEK.

Without the Kydex sheet shavings, a relatively fast-acting capillary solvent can be made by using 50/50 THF and MEK mixture. THF works well at 100%, but it tends to flash off too quickly resulting in a poor joint. The addition of MEK slows down the evaporation rate and affords greater time to work with the joint.

Reference: *Bonding Kydex Sheet to Kydex Sheet*, Supplier technical brief (TB-103A), Kleerdex Company, 2007.

40.2.5 Adhesive Bonding

Kleerdex: Kydex (form: sheet)

Cyanoacrylate adhesives, such as Loctite's Super Bonder 400 series instant adhesive, yields very high joint strength for bonding Kydex sheet to itself and to other materials. In general, these are clear adhesives. They are especially suitable for smaller areas of application, where a very fast cure is desired.

The based adhesives by IPS work well for Kydex sheet applications. Any of the following IPS Weld-On adhesives can be used: #4052, #4007 and #1007. These adhesives also work well for Kydex sheet to PVC and ABS applications.

Acrylic-based adhesives, such as Devcon's 'Plastic Welder' or 'Plastic Welder II' can be used to form very strong bonds with Kydex sheet. The Welders produce a strong bond, which cures in about 15 minutes; the adhesive is white in color. There is a 'Flex Welder', which produces a somewhat flexible bond which cures in roughly 30 minutes. Flex Welder is yellow in color, although it does not give as good a bond as the Plastic Welder and Plastic Welder II. There is also a 'Composite Welder' that is good for bonding one composite to another, such as Kydex sheet to another plastic or metal. The 'Composite Welder' is blue/green in color. When using adhesives, be sure to join your substrates immediately after applying the adhesive since they have a fast cure time.

Extreme Adhesives, a branch of the Adhesive Engineering & Supply, offer 'Extreme 310' in black and white, which is comparable to Plastic Welder.

Most hardware stores carry an adhesive for PVC pipe. This type of adhesive usually works well with Kydex sheet, when bonding one smooth side to another. It is important to realize that this adhesive does not work well for structural use and should be only used as a cosmetic adhesive.

Reference: *Bonding Kydex Sheet to Kydex Sheet*, Supplier technical brief (TB-103A), Kleerdex Company, 2007.

40.2.6 Mechanical Fastening

Kleerdex: Kydex (form: sheet)

Where rigid fasteners are used, consideration must be given to the thermal expansion differential between Kydex sheet and any other material to which it will be joined. To allow for this differential, oversized holes by 1.60 mm (0.063 inches) in diameter should be drilled into the Kydex sheet. Failure to allow for thermal expansion differentials may result in objectionable buckling during temperature changes.

Where mechanically fastened Kydex sheet assemblies are to be subjected to high stress, the use of nylon or rubber washers or large-headed fasteners are recommended to prevent the fastener heads from pulling through the Kydex sheet. Also, keep in mind that high tension should not be used when riveting Kydex sheet.

Reference: *Mechanically Fastening Kydex Thermoplastic Sheet*, Supplier technical brief (TB-106), Kleerdex Company, 2007.

Kleerdex: Kydex (form: sheet)

Kydex can be mechanically fastened with nails, bolts, rivets and screws to assemblies or hardware. Thin gauges can be fastened by stapling.

Reference: *Physical Properties Kydex 100 Acrylic PVC Alloy Sheet*, Supplier technical report (KC-89-03), Kleerdex Company, 1989.

40.3 PC/ABS Alloy

40.3.1 General

Bayer: Bayblend

Parts molded of Bayblend FR resins may be joined to other parts molded of Bayblend resins, or other plastics or metal parts by any of a variety of techniques. The elasticity of Bayblend FR resins permits the application of snap-fits. This method of assembly is a fast, easy, and an economical way to assemble two or more parts. Bonding or welding may be used for permanent joints. Bolts, screws, or ultrasonic inserts work well for detachable assemblies (Table 40.2).

Table 40.2. Methods of Joining Parts Molded of Bayblend FR PC/ABS

Hinges	Adhesive bonding
Self-tapping screws	Snap-fits
Machine screws	Ultrasonic welding
Molded-in threads	Ultrasonic insertion
Heat insertion	Ultrasonic and heat staking
Heat welding	Ultrasonic spot welding
Electromagnetic welding	Vibration welding
Spin welding	Solvent welding

Reference: *Bayblend FR Resins for Business Machines and Electronics*, Supplier marketing literature (55-D808(5)J 313-10/88), Mobay Corporation, 1988.

40.3.2 Heated Tool Welding

Bayer: Bayblend, Triax

The recommended hot plate welding parameters for Bayblend PC/ABS are:

- Hot plate temperature: 250–410ºC (482–770°F)
- Joining pressure: 0.3–0.9 N/mm^2 (40–130 psi)

The recommended hot plate welding parameters for Triax PC/ABS are:

- Hot plate temperature: 250–410ºC (482–770°F)
- Joining pressure: 0.2–0.9 N/mm^2 (30–130 psi)

Reference: *Hot Plate Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

PC/ABS

Under the right conditions, high strengths (87% of parent) and ductilities (2.4% strain at failure) can be achieved in PC/ABS welds made by the heated tool welding process.

Reference: Stokes VK: Toward a weld-strength database for hot-tool welding of thermoplastics. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

40.3.3 Ultrasonic Welding

Bayer: Bayblend; Triax

At a frequency of 20 kHz, an amplitude of 20–40 µm is recommended for ultrasonic welding of Bayblend; and an amplitude of 25–45 µm is recommended for ultrasonic welding of Triax.

Reference: *Ultrasonic Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

PC/ABS

A weldability study of painted PC/ABS was conducted using a 20 kHz ultrasonic plastic joining process. Design of experiments were used to establish a range of baseline welding conditions for unpainted specimens, and then repeated with painted specimens for comparison. Results showed that PC/ABS can be successfully welded with ultrasonics regardless of whether or not the bonding surfaces have been painted. In this study, weld strengths achieved with painted specimens were less than those of unpainted specimens, more so with the shear joint design.

Reference: St John M, Park JB: Ultrasonic weldability of painted plastics. ANTEC 1997, Conference proceedings, Society of Plastics Engineers, Toronto, May 1997.

Dow Chemical: Pulse 1370

This study was designed to identify which resins could be effectively ultrasonically welded to themselves and other resins, and to identify the maximum bond integrity. Besides looking at the weld strength of various thermoplastic resins, this study explores the effects of gamma radiation and ethylene oxide (EtO) sterilization on the strength of these welds. A wide variety of resins used in the healthcare industry were evaluated including polycarbonate/ABS blends.

The strength of customized “I” beam test pieces was tested in the tensile mode to determine the original strength of each resin in the solid, nonbonded test piece configuration. Data from this base-line testing was used to determine the percent of original strength that was maintained after welding. The most commonly used energy director for amorphous resins, a 90° butt joint, was used as the welding architecture.

Every attempt was made to make this a “real world” study. The aim during the welding process was to create a strong weld, while maintaining the aesthetics of the part. One of the most important factors in determining whether or not a good weld had been achieved was the amount of flash or overrun, noticed along both sides of the joint. Another characteristic of a good weld was a complete wetting of the cross-sectional weld area. The problem here, however, was that only clear polymers used as the top piece, allowed the whole weld to be seen.

Almost all resins involved in the study could be welded together with some degree of success. Overall, it appeared that resin compatibility and the ability to transfer vibrational energy through a part and not similar glass transition temperatures, were the overriding characteristics that led to the best welds. Although not shown in this study, it should be noted that the ability of a resin to be welded is also a function of the architecture of the ultrasonic weld. Some resins that welded well in the architecture used for this study may not weld well with other architectures.

The PC/ABS resin welded fairly well with itself, SAN, ABS, clear RTPU, and the PC. Since neither PC nor ABS bonded very well with the polystyrenes, it was not surprising that the PC/ABS blend did not bond very well either. With the urethanes it appeared that the PC phase was the dominating polymer, since no bonds or weak bonds were the norm. If ABS dominated the weld surface, one would have expected better results based on the bonds achieved between the ABS resins and the urethanes. The EtO or gamma sterilization did not weaken the bonds, outside of the standard deviation, of the polymers tested.

Reference: Kingsbury RT: Ultrasonic weldability of a broad range of medical plastics. ANTEC 1991, Conference proceedings, Society of Plastics Engineers, Montreal, May 1991.

40.3.4 Vibration Welding

Bayer: Bayblend

For linear vibration amplitudes between 0.6 and 0.9 mm (0.024–0.035 inches), and orbital vibration amplitudes between 0.4 and 0.7 mm (0.016–0.028 inches), the recommended welding pressure for Bayblend PC/ABS is between 1 and 2 N/mm^2 (145–290 psi).

Reference: *Vibration Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

GE Plastics: Cycoloy (form: injection-molded plaque)

Based on their respective resin strengths, relative weld strengths of about 83% have been demonstrated in nominally 6.35 mm (0.25 inch) thick specimens of both Cycoloy C1110 and Cycoloy C2950HF. The corresponding failure strains were about 2.3%. However, in the thinner 3.2 mm (0.126 inch) thick specimens of Cycoloy C2950HF, the highest weld strengths attained were about 73%, with a lower strain to failure of about 1.8%. This thickness dependence of weld strength is caused by the highly laminated suface morphology in injection-molded parts made of these materials, the overall effect of which is more noticeable in thinner specimens.

For 6.35 mm (0.25 inch) thick specimens, the maximum relative strength of Cycoloy C1110 to PC welds obtained was 85%, which compares well with the maximum relative weld strength of Cycoloy C1110 to itself, of 83%. In both sets of welds, the strains at failure were about 2.2%. For 3.2 mm (0.126 inch) thick specimens, a lower maximum relative weld strength of 68%, with a strain at failure of 1.8%, was obtained in Cycoloy

C2950HF to PC welds. In comparison with this, the maximum relative weld strength of Cycoloy C2950HF to itself is 72%, with a strain at failure of 1.8%. For 3.2 mm (0.126 inch) thick specimens, Cycoloy C2950HF to ABS welds with relative strengths of 85% have been demonstrated.

Reference: Stokes VK: The vibration welding of polycarbonate/acrylonitrile-butadiene-styrene blends to themselves and to other resins and blends. *Polymer Engineering and Science*, 40(10), p. 2175, October 2000.

GE Plastics: PC/ABS

The achievable strengths of vibration welds of PC/ABS alloy to itself and other thermoplastics are given in Table 40.3.

Reference: Stokes VK: Toward a weld-strength data base for vibration welding of thermoplastics. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

40.3.5 Solvent Welding

Bayer: Bayblend

You can weld parts made of Bayblend resins using methylene chloride or ethylene dichloride. Methylene chloride's fast evaporation rate helps to prevent solvent-vapor entrapment for simple assemblies. For complex assemblies that require more curing time, use ethylene dichloride because it has a slower evaporation rate, allowing for longer assembly times. Mixing methylene chloride and ethylene dichloride in a 60:40 solution, a commonly used mixture, will give you a longer time to assemble parts than pure methylene chloride because of the reduced evaporation rate.

When using solvent welding techniques with Bayblend, some embrittlement may occur. Parts can lose some of their excellent impact strength at the weld joint.

A 5–10% solution of polycarbonate in methylene chloride helps to produce a smooth, filled joint when the mating parts made of Bayblend resin do not fit perfectly. Do not use this mixture to compensate for severely mismatched joints. Increasing the concentration can result in bubbles at the joint.

When working with polycarbonate blends, curing parts for elevated-service use and maximum bond strength is much more complicated. You may have to use a complicated treatment schedule of gradually increasing temperatures for these applications (see Table 40.4).

Table 40.3. Achievable Strengths of Vibration Welds of PC/ABS Alloy to Itself and Other Thermoplastics

Material Family	PC/ABS		
Tensile strength[b], MPa (ksi)	60 (8.7)		
Elongation @ break[b], %	4.5		
Specimen thickness, mm (in.)	3.2 (0.125)	3.2 (0.125)	6.3 (0.25)
Mating Material			
Material family[a]	ABS	PC	PC/ABS
Tensile strength[b], MPa (ksi)	44 (6.4)	68 (9.9)	60 (8.7)
Elongation @ break[b], %	1.8	6	4.5
Specimen thickness, mm (in.)	3.2 (0.125)	3.2 (0.125)	6.3 (0.25)
Process Parameters			
Process type	Vibration welding		
Weld frequency	120 Hz		
Welded Joint Properties			
Weld factor (weld strength/weaker virgin material strength)	0.85	0.7	0.85
Elongation @ break[b], % (nominal)	1.8	1.8	2.3

[a] ABS: acrylonitrile-butadiene-stryrene copolymer; PC: polycarbonate; PC/ABS: polycarbonate/ABS alloy.
[b] Strain rate of $10^{-2}s^{-1}$

Reference: *Engineering Polymers. Joining Techniques. A Design Guide*, Supplier design guide (5241 (7.5M) 3/01), Bayer Corporation, 2001.

40.3.6 Adhesive Bonding

PC/ABS

The compatibility of generic adhesive groups with PC/ABS alloys is shown in Table 40.5.

Reference: *Techniques: Adhesive Bonding, Solvent Bonding, and Joint Design*, Supplier technical report (#SR-401A), Borg-Warner Chemicals, Inc., 1986.

Table 40.4. Solvent Bond Curing Schedule for Bayblend Resins

Sequential Holding Time, hours	Part or Bond Temperature, °F (°C)
8	73 (23)
12	100 (40)
12	150 (65)
12	200 (93)
12	225 (110)

40.3.7 Mechanical Fastening

Bayer: Bayblend FR-110

Tapping and Self-tapping Screws: Table 40.6 lists some average pull-out forces and various torque data for thread-cutting screws tested in Bayblend PC/ABS resin. For this data, the screws were installed in the manufacturer's suggested hole diameters. The screw boss outer diameter was approximately twice the screw outer diameter.

Reference: *Engineering Polymers. Joining Techniques. A Design Guide*, Supplier design guide (5241 (7.5M) 3/01), Bayer Corporation, 2001.

40.4 PC/PBT Alloy

40.4.1 Heated Tool Welding

PC/PBT

Under the right conditions, very high strengths (98% of parent) and ductilities (4.1% strain at failure) can be achieved in PC/PBT welds made by the heated tool welding process.

Table 40.5. Compatibility of Generic Adhesive Groups with Polycarbonate/ABS Alloys

Characteristic Evaluated	Material Evaluated	Compatibility Ratings for Generic Adhesive Groups[a]				
		Acrylics	Urethanes	Cyanoacrylates[b]	Epoxies	Silicones
Strength	Proloy PC/ABS	1	4	3	3	5
Impact resistance	Proloy PC/ABS	2	1	5	4	4
Gap filling	Proloy PC/ABS	2	1	5	3	1
Cure time	Proloy PC/ABS	2	5	1	3	3
Ease of application	Proloy PC/ABS	3	4	1	3	2

[a] Compatibility rating guide: 1: excellent, 2: very good, 3: good, 4: fair, 5: poor. These ratings are generalizations and will differ for specific brands. Chemical compatibiliity should be evaluated prior to adhesive selection to prevent stress cracking.

[b] Stress cracking is a concern with cyanoacrylates. Careful evaluation of chemical compatibility with the substrate is recommended.

Table 40.6. Thread-Cutting Screw Data for Bayblend FR-110 PC/ABS Resin

Screw Size & Type	Screw Length, in. (mm)	Hole Diameter, in. (mm)	Drive Torque, lb in. (Nm)	Recommended Tightening Torque, lb in. (Nm)	Stripping Torque, lb in. (Nm)	Screw Pull-Out, lbf (N)
#6, Type 23	0.375 (9.5)	0.120 (3.0)	3.3 (0.37)	5.6 (0.63)	10.15 (1.14)	349 (1552)
#6, Type 25	0.500 (12.7)	0.120 (3.0)	3.3 (0.37)	7.9 (0.89)	17.16 (1.93)	308 (1370)
#8, Type 23	0.500 (12.7)	0.136 (3.5)	4.9 (0.55)	8.4 (0.95)	15.5 (1.75)	479 (2130)
#8, Type 25	0.562 (14.3)	0.146 (3.7)	4.2 (0.47)	11.5 (1.3)	26.2 (2.96)	512 (2277)

Reference: Stokes VK: Toward a weld-strength database for hot-tool welding of thermoplastics. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

40.4.2 Vibration Welding

GE Plastics: Xenoy 1102 (form: 3.2 mm (0.126 inch) thick injection-molded plaque)

PC/PBT has been shown to weld well with PBT; welds with strengths of 98% of the strength of PC/PBT have been demonstrated for the following welding conditions: frequency of 120 Hz, amplitude of 3.175 mm (0.125 inches), pressure of 0.90 MPa (130 psi), weld penetration of 0.56 mm (0.022 inches) and a weld time of 1.7 seconds.

PC/PBT welds fairly well to M-PPO; welds can attain about 73% of the strength of M-PPO using the following welding conditions: frequency of 120 Hz, amplitude of 3.175 mm (0.125 inches), pressure of 0.90 MPa (130 psi), weld penetration of 0.55 mm (0.022 inches) and a weld time of 2.0 seconds.

PC/PBT welds very poorly to PPO/PA; for practical purposes, these two materials do not weld.

Reference: Stokes VK: The vibration welding of poly (butylene terephthalate) and a polycarbonate/poly(butylene terephthalate) blend to each other and to other resins and blends. *Journal of Adhesion Science and Technology*, 15(4), p. 499, 2001.

GE Plastics: PC/PBT

The achievable strengths of vibration welds of PC/PBT alloy to itself and to polycarbonate are given in Table 40.7.

Reference: Stokes VK: Toward a weld-strength data base for vibration welding of thermoplastics. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

40.5 PC/PCT Alloy

40.5.1 Solvent Welding

Eastman: Ektar MB DA003 (features: transparent)

In tests conducted to evaluate the bondability/compatibility of plasticized PVC tubing to rigid, transparent thermoplastics, the PCTG-PC blend exhibited adequate weld strengths when welded with cyclohexanone or with 50:50 blends of either MEK or methylene chloride in cyclohexanone. Greater amounts of MEK or methylene chloride decrease the weld strength. The THF and 1,2-dichloroethane data both show variances that earned a marginal rating. Acetone performed inadequately with PCTG-PC with respect to both weld strength and ease of insertion. The presence of more than 50% methylene chloride also increased the difficulty of assembly. However, no crazing was observed in conjunction with any of the solvents. The suggested solvent mix is methylene chloride in cyclohexanone in 50:50 proportions.

Reference: Haskell A: Bondability/compatibility of plasticized PVC to rigid, transparent thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

40.6 PC/PET Alloy

40.6.1 Ultrasonic Welding

Bayer: Makroblend UT400

Tensile test bars (12.8 mm (0.504 inch) width and 3.2 mm (0.126 inch) thickness) having a molded-in

Table 40.7. Achievable Strengths of Vibration Welds of Polycarbonate/Polyester PBT Alloy to Itself and to Polycarbonate

Material Family	**PC/PBT**	
Tensile strength[b], MPa (ksi)	50 (7.3)	
Specimen thickness, mm (in.)	6.3 (0.25)	
Mating Material		
Material family[a]	PC	PC/PBT
Tensile strength[b], MPa (ksi)	68 (9.9)	50 (7.3)
Elongation @ break[b], %	6	
Specimen thickness, mm (in.)	3.2 (0.125)	6.3 (0.25)
Process Parameters		
Process type	Vibration welding	
Weld frequency	120 Hz	
Welded Joint Properties		
Weld factor (weld strength/ weaker virgin material strength)	1.0	1.0
Elongation @ break[b], % (nominal)	4.9	>15

[a] PC: polycarbonate; PC/PBT: polycarbonate/PBT alloy.
[b] Strain rate of $10^{-2}s^{-1}$.

energy director were ultrasonically welded in the following two modes under 18 different conditions: constant energy mode with variable force triggering and time based mode with delay timer triggering. The experimental conditions were set up according to the L18 orthogonal array of Taguchi statistical experimental design. It should be pointed out that the angle of the energy director and delay timer setting have been assigned in the array such that their interaction can be analyzed. After welding, pull strength of the welded test bars was determined at a pull rate of 50 mm/min (1.97 inches/minute).

A few key highlights of the results are that impact modified PC/PET blend can successfully be welded under a broad range of welding conditions; and the constant energy mode has yielded more consistent values than the time-based mode. A similar conclusion has also been obtained from PC welding experiments carried out under comparable experimental conditions.

In the constant energy mode, the energy director angle was found to interact strongly with the delay timer setting. For the best pull strength, the 60° energy director required a long delay timer setting (0.3 seconds), while the 90° energy director required a short delay timer setting (0.1 seconds). Also, it has been found that the higher the energy set value, the higher is the pull strength.

In contrast to the constant-energy mode, the interaction of the energy director with the delay timer setting in the time-based mode did not provide a simple trend. An interesting result from the time-based mode experiment is that the best pull strength was obtained from the longest weld timer setting.

The optimum welding conditions for impact modified PET/PC blend are shown in Table 40.8. There is a significant difference in optimum welding conditions for the constant energy mode and time-based mode: the hold pressure setting of the former mode is significantly lower than in the latter mode (62 vs. 104 kPa; 9 vs. 15 psi). This may indicate that the constant energy mode yields a more effective melting of the resin than the time-based mode.

Reference: Chung JY, Charles JJ: Properties of an impact modified polycarbonate/polyethylene terephthalate blend. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

40.6.2 Solvent Welding

Bayer: Makroblend

Do not use solvent welding with parts made of Makroblend resins. Because of Makroblend's polyester component and the resulting high chemical resistance, aggressive solvents must be used for welding. These solvents can cause low weld strength.

Reference: *Engineering Polymers. Joining Techniques. A Design Guide*, Supplier design guide (5241 (7.5M) 3/01), Bayer Corporation, 2001.

40.7 PPO/PA Alloy

40.7.1 Heated Tool Welding

PPO/PA

Under the right conditions, very high strengths (100% of parent) and ductilities (4.5% strain at failure) can be achieved in PPO/PA welds made by the heated tool welding process.

Reference: Stokes VK: Toward a weld-strength database for hot-tool welding of thermoplastics. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

Table 40.8. Optimum Ultrasonic Welding Conditions for Impact Modified Polyester PET/Polycarbonate Blend

Mode	Welding Parameter	Energy Director	
		60°	90°
Constant energy mode	Energy set value (J)	260	260
	Delay timer (s)	0.3	0.1
	Hold timer (s)	0.25	0.25
	Hold pressure (kPa)	62	62
Time-based mode	Weld timer (s)	0.5	0.5
	Delay timer (s)	0.2	0.3
	Hold timer (s)	0.65	0.65
	Hold pressure (kPa)	104	104

40.7.2 Vibration Welding

GE Plastics: Noryl GTX 910 (form: 6.35 mm (0.25 inch) thick injection-molded plaque)

Welds were made at a frequency of 120 Hz, a weld amplitude of 3.175 mm (0.125 inches), weld penetrations between 0.13 and 1.27 mm (0.005–0.050 inches) and weld pressures between 0.90 and 6.89 MPa (130–1000 psi).

Results showed that Noryl GTX 910 welds exceptionally well. Even at the lower weld pressure of 0.90 MPa (130 psi), relative weld strengths (ratio of weld strength to ultimate strength of the material) greater than 90% could easily be obtained, and the corresponding strains-to-failure were quite high. At the higher weld pressures of 3.45 and 6.89 MPa (500–1000 psi), the weld strengths were uniformly high at all the penetrations considered; the corresponding strains-to-failure were also exceptionally high. The fact that the relative weld strength was greater than 100% at these pressures can be attributed to two factors: first, at the higher weld pressures the weld zone thickens due to a 'forging' effect, so that the load-carrying area increases. Second, the weld strengths were normalized by a mean resin strength, so that strength variations in the base resin can cause the relative weld strengths to exceed 100%.

The very high strength achievable in welds of PPO/PA is, most likely, a reflection of the high weld strength achievable in PA 6,6, the continuous phase in this blend.

Reference: Stokes VK: Vibration weld strength data for poly(phenylene oxide)/polyamide blend. *Journal of Adhesion Science and Technology*, 17(9), p. 1161, 2003.

GE Plastics: Noryl GTX 910 (form: 3.2 mm (0.126 inch) thick injection-molded plaque)

PPO/PA does not weld to PBT and, for practical purposes, does not weld to PC/PBT.

Reference: Stokes VK: The vibration welding of poly (butylene terephthalate) and a polycarbonate/poly(butylene terephthalate) blend to each other and to other resins and blends. *Journal of Adhesion Science and Technology*, 15(4), p. 499, 2001.

GE Plastics: Modified PPE/PA Alloy

The achievable strengths of vibration welds of polystyrene modified polyphenylene ether/nylon alloy to itself and other thermoplastics are given in Table 40.9.

Table 40.9. Achievable Strengths of Vibration Welds of Polystyrene Modified Polyphenylene Ether/Nylon Alloy to Itself and Other Thermoplastics

Material Family	M-PPO/PA		
Tensile strength[b], MPa (ksi)	58 (8.5)		
Elongation @ break[b], %	>18		
Specimen thickness, mm (in.)	6.3 (0.25)		
Mating Material			
Material family[a]	M-PPO/PA	M-PPO	PC
Tensile strength[b], MPa (ksi)	58 (8.5)	45.5 (6.6)	68 (9.9)
Elongation @ break[b], %	>18	2.5	6
Specimen thickness, mm (in.)	6.3 (0.25)	6.3 (0.25)	6.3 (0.25)
Process Parameters			
Process type	Vibration welding		
Weld frequency	120 Hz		
Welded Joint Properties			
Weld factor (weld strength/weaker virgin material strength)	1.0	0.22	0.29
Elongation @ break[b], % (nominal)	>10	0.35	0.75

[a] M-PPO: modified polyphenylene oxide; M-PPO/PA: modified polyphenylene oxide/polyamide alloy; PC: polycarbonate.
[b] Strain rate of $10^{-2}s^{-1}$.

Reference: Stokes VK: Toward a weld-strength data base for vibration welding of thermoplastics. ANTEC 1995, Conference proceedings, Society of Plastics Engineers, Boston, May 1995.

40.7.3 Solvent Welding

GE Plastics: Noryl GTX (Polystyrene modified polyphenylene ether/nylon 6 alloy)

The Noryl GTX grades may not perform as well with solvent welding as the standard Noryl resins. For these grades, another method such as ultrasonic welding is preferred.

Reference: *Noryl Design Guide*, Supplier design guide (CDX-83D (11/86) RTB), General Electric Company, 1986.

40.8 PPO/PPS Alloy

40.8.1 Vibration Welding

PPO/PPS

For weld pressures in the range 0.52–1.72 MPa (75–250 psi), the highest weld strength was attained at the higher weld frequency of 240 Hz for the 50 wt.% PPO/50 wt.% PPS blend. The highest relative weld strengths (and corresponding failure strains) obtained were 85.5% (1.75%) at a weld pressure of 1.72 MPa (250 psi). At 240 Hz, the weld strength continued to increase with pressure, thus still higher weld strengths may be possible at higher weld pressures.

Reference: Stokes VK: The vibration welding of poly (phenylene oxide)/poly(phenylene sulfide) blends. *Polymer Engineering and Science*, 38(12), p. 2046, December 1998.

41 Thermoplastic Elastomers

41.1 Olefinic Thermoplastic Elastomer

41.1.1 General

DSM: Sarlink 4000 (applications: automotive, building industry; features: improved elastic properties)

Thermal welding techniques, which form high strength joints, are suitable for Sarlink. Sarlink grades are easily thermally welded to themselves, or to other nonpolar polymers such as polyolefins.

Reference: *Sarlink Typical Properties of Thermoplastic Elastomer Grades*, Supplier marketing literature (8/95 (4000)), DSM Elastomers, 1995.

41.1.2 Heated Tool Welding

TPO

This study focused on the weldability of two specific thermoplastic polyolefins (TPOs) using heated tool welding. A three-factor (heating temperature, heating time, and welding pressure) and three-level design matrix was used. Results showed that the two TPO materials could be successfully welded by heated tool welding. It was found that the maximum joint strength was 86% of the bulk material strength.

While heated tool welding provided stronger joints compared to vibration welding, it had a longer cycle time.

Reference: Wu CY, Mokhtarzadeh A, Rhew M, Benatar A: Heated tool welding of thermoplastic polyolefins (TPO). ANTEC 2003, Conference Proceedings, Society of Plastics Engineers, Nashville, May 2003.

41.1.3 Ultrasonic Welding

TPO

The optimal welding parameters were found to be:

- Melt-down distance: 0.75 mm (0.030 inches).
- Welding force: 300 N (67 lbf).
- Hold time: 2.0 seconds.

It was found that paint layers at the welded joint affected the material weld strength significantly. Tested material required a high machine power to achieve the higher weld strengths.

Reference: Park J, Liddy J: Effect of paint over spray for vibration and ultrasonic welding process. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

TPO

A design of experiments was performed to determine the optimal ultrasonic welding process parameter set-up conditions, robustness of the optimal set-up conditions, and the average weld strength with different reground contents.

Two types of reground materials (regrinds from unpainted and painted substrates) were generated to investigate if the paint content in regrinds makes any difference in welding. However, differences in strength and power requirements were insignificant.

Under optimized weld parameter set-up conditions described in Table 41.1, the highest weld strength was achieved at the virgin material plaque welds and weld strength was decreased as more regrind content was included in the plaques. The 100% regrind plaque resulted in about 10% decrease in the weld strength. Considering the amount of regrind content, it was found that the tested TPO was very tolerable of allowing the

Table 41.1. Optimal Set-up Conditions for Ultrasonic Welding of TPO

Welding parameter	Optimal set-up condition
Melt-down distance (mm)[a]	0.75
Welding force (N)[b]	300
Hold time (s)	2.0
Amplitude (%)[c]	100

[a] Melt-down distance is an absolute distance, which is determined after contact pressure between horn and plaque reaches a trigger force level of 300 N (67 lbf).

[b] Weld pressure can be calculated by weld force divided by cross-sectional area of the air cylinder. For this machine, the air cylinder diameter was 40 mm (1.6 inches).

[c] 100% amplitude set-up generated 0.01456 mm (0.00057 inches) at 35 kHz frequency.

usage of the reground material in the ultrasonic welding process.

Average weld strengths of the paint over-sprayed plaques containing 40% of painted and unpainted regrinds were 378 and 358 N (85.0 and 80.5 lbf), respectively. Comparing weld strength (442 N; 99.4 lbf) of the regular weld plaques with the 40% painted regrind, 14%, and 19% decreases in weld strengths of painted and unpainted regrind plaques were found, respectively.

Under the same melt-down (collapse) distance, less melting was observed for the paint over-spray plaques than for the regular plaques. This is mainly because a significant amount of energy was dissipated in overcoming the paint layer on the over-sprayed plaques. Accordingly, the lower weld strength was produced for the paint over-sprayed plaques.

Reference: Park J, Liddy J: Design of experiments (DOE) procedures to evaluate ultrasonic weldability of materials. ANTEC 2000, Conference proceedings, Society of Plastics Engineers, Orlando, May 2000.

41.1.4 Vibration Welding

TPO

The optimal welding parameters were found to be:

- Melt-down distance: 1.4 mm (0.055 inches).
- Welding pressure: 2.3 MPa (330 psi).
- Hold time: 3.0 seconds.

It was found that paint layers at the welded joint did not affect the material weld strength significantly. The vibration welding process has a robust self-cleaning mechanism during welding to overcome a paint layer at the welded joint.

Reference: Park J, Liddy J: Effect of paint over spray for vibration and ultrasonic welding process. ANTEC 2004, Conference Proceedings, Society of Plastics Engineers, Chicago, May 2004.

ATC Polymers (filler: talc; features: hard; form: 3.2 mm (0.13 inch) thick injection-molded plaque)

A 3-factorial, 2-level full factorial DOE was performed. It was found that the weld time was a strong function of vibration amplitude. In addition, high vibration amplitude reduced the time needed to reach a specific melt-down. In contrast, high pressure increased the time needed to reach a specific melt-down. This may result from high pressure constraining movement during solid friction heating, as well as the shear thinning effect during viscous heating.

The maximum T-joint strength for a 25 × 3.2 mm (0.98 × 0.13 inch) sample was 1323 N (297 lbf), which is about 60% of the base material tensile strength.

Reference: Wu CY, Trevino L: Vibration welding of thermoplastic polyolefins. ANTEC 2002, Conference proceedings, Society of Plastics Engineers, San Francisco, May 2002.

41.1.5 Laser Welding

TPO (form: 2 mm (0.08 inch) thick injection-molded plaque)

Laser welding trials were carried out between a dynamic cross-linking type polyolefin elastomer (TPV) as a transmission material and talc-reinforced PP as an absorption material. The laser had a wavelength of 940 nm, a power output of 10–50 W, a scanning rate of 10 mm/s (0.4 inches/s) and a spot size of 1.0 mm (0.04 inches) diameter. The welding pressure was 0.4 MPa (58 psi).

Blending a transmitting black colorant into the TPV generated better weld strength than the case without addition, since it prevents excessive thermal generation in the absorption resin.

Reference: Isoda A, Hatase Y, Nakagawa O, Yushina H: Laser transmission welding of colored thermoplastic elastomers and hard plastics. ANTEC 2006, Conference proceedings, Society of Plastics Engineers, Charlotte, May 2006.

DuPont Dow Elastomers: Engage (form: 3 mm (0.12 inch) thick injection-molded tensile specimen bars)

Through transmission laser welding was carried out using a 100 W average power Ytterbium fiber laser. The beam was collimated to a 5 mm (0.2 inch) diameter and delivered to the workpiece without focusing the beam. A 3-factor 2-level full factorial design of experiments was utilized to determine the weldability of polyolefin elastomer (POE) to TPO. The factors considered were laser power, speed, and clamping pressure. The welds were subjected to a lap shear test for qualification of their relative strengths.

Power and speed were the most significant factors in regards to their strength and also had a significant interaction for all POEs. Increasing the power and decreasing the speed tended to increase joint strength. A small increase in power could accommodate a larger increase in speed in order to maintain constant strength. Pressure had little effect of soft and medium POE and had no effect on hard POE.

The weld strength of POE to TPO had a tendency to the ultimate tensile strength of POE.

Reference: Wu CY, Douglass DM: Fiber laser welding of elastomer to TPO. ANTEC 2004, Conference proceedings, Society of Plastics Engineers, Chicago, May 2004.

Basell Polyolefins: TPO (form: 3.2 mm (0.126 inch) thick injection-molded plaques)

In order to understand the weldability of different-colored TPO to PP using laser welding, a three-factor (laser power, welding time, and scanning speed), two-level full factorial design of experiments was performed. Natural PP copolymer from Basell Polyolefins was used as the transparent layer. Three TPO materials (black, blue, and tan), consisting of PP, talc filler, and rubber modifiers, were used as the absorbing layer. The samples were welded using a 200 W flashlamp-pumped Nd:YAG laser with a wavelength of 1.06 μm.

It was found that the 3.2 mm (0.126 inch) thick natural PP had a transmission rate of 29%. It was also found that the black TPO had the most laser absorption, followed by the blue, and then the tan. Therefore, the black TPO required the least amount of welding time to reach the maximum joint strength. In addition, as the scanning speed was reduced, the time required to reach maximum joint strength was also reduced.

Reference: Wu CY, Cherdron M, Douglas DM: Laser welding of polypropylene to thermoplastic polyolefins. ANTEC 2003, Conference proceedings, Society of Plastics Engineers, Nashville, May 2003.

41.1.6 Adhesive Bonding

DSM: Sarlink 4000 (applications: automotive, building industry; features: improved elastic properties)

Highly polar substances tend to form better adhesive bonds than those with low polarity, such as the polyolefinic Sarlink 4000 series. Good adhesion can be obtained with the Sarlink 4000 series by the use of solvent based, chemically activated systems at elevated temperatures.

Reference: *Sarlink Typical Properties of Thermoplastic Elastomer Grades*, Supplier marketing literature (8/95 (4000)), DSM Elastomers, 1995.

41.2 Polyester Thermoplastic Elastomer

41.2.1 General

BASF: Ecoflex (features: biodegradable)

Ultrasonic welding and high frequency welding are fundamentally suitable for Ecoflex F.

Reference: *Ecoflex Biodegradable Plastic*, Supplier design guide, BASF.

41.2.2 Heated Tool Welding

DuPont: Hytrel

All grades of Hytrel may be used for hot plate welding; however, it may be difficult to achieve a good weld with blow molding grades such as HTR4275. This is because the low melt flow makes it more difficult for the two melted surfaces to flow together. If this problem occurs, higher temperatures, up to 280°C (536°F), may help. The plate surface temperature should be 20–50°C (36–90°F) above the melting point of the Hytrel grade.

Table 41.2 shows results obtained when several other thermoplastic materials were hot plate welded to Hytrel. Plate temperatures were normally 300°C (572°F) with melt and weld times of 7–9 seconds.

Heated wedge welding has been successfully used for factory prefabrication of Hytrel sheeting for tank liners.

Reference: *Hytrel Thermoplastic Polyester Elastomer Design Guide*, Supplier design guide (H-81098), DuPont Company, 2000.

41.2.3 Ultrasonic Welding

DuPont: Hytrel

Sonic welding is a satisfactory way to assemble parts fabricated from the harder types of Hytrel. The

Table 41.2. Hot Plate Welding of Hytrel to Other Thermoplastic Materials

Good Weld	Questionable	No Weld
Polycarbonate	Styrene	ABS
SAN	PES	Polypropylene
Cellulose acetate	EVA	Nylon 6,6
PVC		Polyethylene
		Acrylic

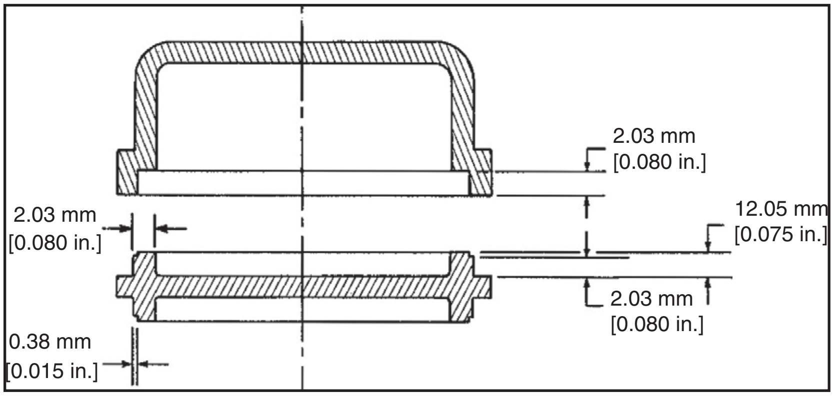


Figure 41.1. An automotive valve component designed for ultrasonic assembly using Hytrel polyester thermoplastic elastomer.

design for an automotive valve component is a good example (Fig. 41.1). The step joint is placed on the exterior of the lower part. The web of the lower part will then retain or support the diameter of the weld surface, and the mating weld surface on the upper part can be retained by an encircling fixture. This overcomes the possibility of the weld surface on the upper part distorting inwardly. This distortion, of course, could affect the weld strength. Make the axial length of the upper weld surface, 2.03 mm (0.08 inches), greater than the axial length of the lower weld surface, 1.9 mm (0.075 inches), to ensure that the parts will bottom out on the welding line.

The following considerations are important in determining the applicability of this method to Hytrel:

- Hytrel requires high-power input because of its flexibility.
- If different grades of Hytrel are being assembled, the melting points of these grades should differ by no more than 10–15ºC (18–27ºF).

Reference: *Hytrel Thermoplastic Polyester Elastomer Design Guide*, Supplier design guide (H-81098), DuPont Company, 2000.

41.2.4 Vibration Welding

DuPont: Hytrel

For rigid parts with a large weld area, the preferred assembly method is vibration welding. As an example, the carbon cannister used for automotive fuel vapor emission control is an ideal candidate (Fig. 41.2). Since it is rectangular, spin welding is not practical; its large weld area precludes the use of sonic welding because of the need for a high energy source, and a hermetic seal is required. The type of vibration weld used in this case is linear, the cover plate and body moving relative to each other along an axis down the long centerline of the open end of the body. The flange which forms the weld surface is ribbed to maintain proper flatness during the welding operation. Clearance is allowed between the recessed portion of the cover and the inside of the body.

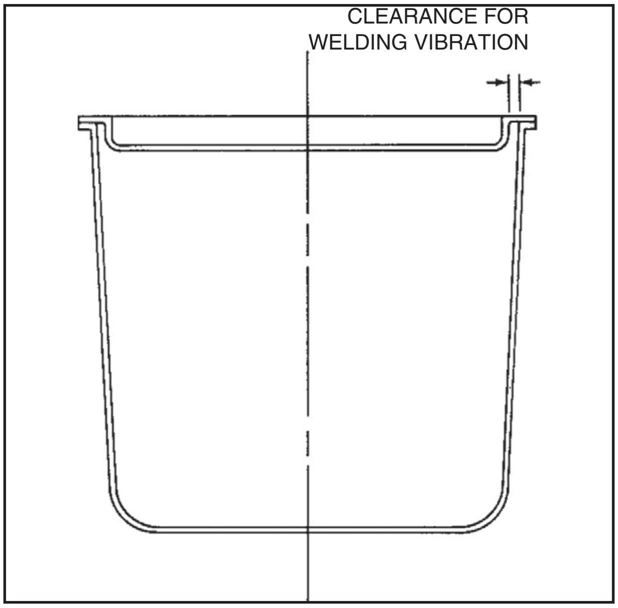


Figure 41.2. Automotive carbon canister design for vibration welding assembly using Hytrel polyester thermoplastic elastomer.

Reference: *Hytrel Thermoplastic Polyester Elastomer Design Guide*, Supplier design guide (H-81098), DuPont Company, 2000.

41.2.5 Radio Frequency Welding

DuPont: Hytrel

High frequency welding can generally only be applied to sheet welding (up to 1.5 mm (0.06 inches)) but is very suitable for factory welding. For Hytrel, which has a lower dielectric loss than other plastics, the optimum electrode area for a 1.5 kW machine is about 150 × 12 mm (5.9 × 0.5 inches), that is, 1800 mm^2 (2.95 $inches^2$). The maximum sheet thickness that can be easily welded with a 1.5 kW machine is approximately 1.5 mm (0.06 inches). Hytrel requires higher voltage or smaller electrodes than PVC. Weld times are typically between 3 and 8 seconds, depending on the grade of Hytrel, thickness, etc. A heated (temperature-controlled) electrode is best for consistent results, because the power setting required for a particular material type and thickness depends on the electrode temperature.

The 40D and 55D grades have been very successfully welded by this method. Harder grades of Hytrel sheet, up to 1 mm (0.04 inches) thick may be welded, but longer time may be required.

Reference: *Hytrel Thermoplastic Polyester Elastomer Design Guide*, Supplier design guide (H-81098), DuPont Company, 2000.

41.2.6 Hot Gas Welding

DuPont: Hytrel

Hot air welding can be used for sealing Hytrel sheeting (0.5–1.5 mm; 0.02–0.06 inches) in applications such as tank and pit liners. This technique is only suitable for certain grades of Hytrel, such as 4056, G4075, and 5556. Very high or very low melt flow grades (e.g., 5526 and HTR4275), as well as those with additives such as 10 MS, have been found to be difficult to weld by this method.

Reference: *Hytrel Thermoplastic Polyester Elastomer Design Guide*, Supplier design guide (H-81098), DuPont Company, 2000.

41.2.7 Extrusion Welding

DuPont: Hytrel

Good welds have been produced with several grades of Hytrel sheeting, including those containing 10 MS.

Reference: *Hytrel Thermoplastic Polyester Elastomer Design Guide*, Supplier design guide (H-81098), DuPont Company, 2000.

41.2.8 Mechanical Fastening

DuPont: Hytrel

Snap-fits: The suggested allowable strains for lug type snap-fits are given in Table 41.3.

Reference: *DuPont Engineering Polymers. General Design Principles—Module I*, Supplier design guide, DuPont Company, 2002.

41.3 Polyurethane Thermoplastic Elastomer

41.3.1 General

BASF: Elastollan

The following welding techniques have proved successful for the joining of finished and semifinished Elastollan parts:

- Injection molded parts are mainly joined by hot plate, ultrasonic (harder types), high frequency or friction welding.
- For semifinished parts and profiles, hot plate or friction welding as well as hot gas welding is used.
- For films, best results are achieved by thermal sealing, heat impulse welding, or high frequency welding.

Reference: *Elastollan Processing Recommendations*, Supplier technical information (Z/M, Fro 208-2-05/GB), BASF, 2005.

41.3.2 Heated Tool Welding

Bayer: Desmopan

The recommended hot plate welding parameters for Desmopan are:

- Hot plate temperature: 270–320ºC (518–608°F).
- Joining pressure: 0.3–1.0 N/mm^2 (44–145 psi)

Table 41.3. Suggested Allowable Strains for Lug Type Snap-fits in Hytrel Resins

	Allowable strain (%)	
Material	**Used once (new material)**	**Used frequently**
Hytrel	20	10

Reference: *Hot Plate Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

41.3.3 Ultrasonic Welding

Bayer: Desmopan

Desmopan types absorb ultrasonic vibrations to a high degree on account of their high damping factor. This causes internal heating of the component, and reduces the vibration energy arriving at the joint.

Reference: *Ultrasonic Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

Dow Chemical: Pellethane 2363-55D (features: 55 Shore D hardness); **Pellethane 2363-75D** (features: medical grade, 75 Shore D hardness)

This study was designed to identify which resins could be effectively welded to themselves and other resins, and to identify the maximum bond integrity. Besides looking at the weld strength of various thermoplastic resins, this study explores the effects of gamma radiation and ethylene oxide (EtO) sterilization on the strength of these welds. A wide variety of resins used in the healthcare industry were evaluated, including thermoplastic polyurethanes.

The strength of customized "I" beam test pieces was tested in the tensile mode to determine the original strength of each resin in the solid, nonbonded test piece configuration. Data from this base-line testing was used to determine the percent of original strength that was maintained after welding. The most commonly used energy director for amorphous resins, a 90° butt joint, was used as the welding architecture.

Every attempt was made to make this a "real world" study. The aim during the welding process was to create a strong weld, while maintaining the aesthetics of the part. One of the most important factors in determining whether or not a good weld had been achieved was the amount of flash or overrun noticed along both sides of the joint. Another characteristic of a good weld was a complete wetting of the cross-sectional weld area. The problem here, however, was that only clear polymers used as the top piece allowed the whole weld to be seen.

Overall, it appeared that resin compatibility and the ability to transfer vibrational energy through a part, and not similar glass transition temperatures, were the overriding characteristics that led to the best welds. Although not shown in this study, it should be noted that the ability of a resin to be welded is also a function of the architecture of the ultrasonic weld. Some resins that welded well in the architecture used for this study may not weld well with other architectures.

The two TPUs in this study did not bond well with either the polystyrenes, the polycarbonates, or the PC/ABS blend. The more rigid of the two resins, the 75D material, bonded quite well to itself, the RTPUs, and the ABS. The softer, 55D TPU, did not bond well with anything. This was caused by the soft flexible nature of the polymer. It absorbed the vibrational energy, instead of converting it into frictional heat at the energy director. In the initial stages of this study, including a softer, 80 shore A, TPU was considered, but no welds could be achieved with this material. The EtO and gamma sterilization had little effect on the TPU resins in this study.

Reference: Kingsbury RT: Ultrasonic weldability of a broad range of medical plastics. ANTEC 1991, Conference Proceedings, Society of Plastics Engineers, Montreal, May 1991.

41.3.4 Vibration Welding

Bayer: Desmopan

For linear vibration amplitudes between 0.6 mm (0.024 inches) and 0.9 mm (0.035 inches), and orbital vibration amplitudes between 0.4 mm (0.016 inches) and 0.7 mm (0.027 inches), the recommended welding pressure for Desmopan (hard types only) is between 1 and 2 N/mm^2 (145–290 psi). The soft Desmopan types do not have the necessary inherent stability, and thus tend to vibrate as well, making them unsuitable for vibration welding.

Reference: *Vibration Welding*, Supplier design guide, Bayer MaterialScience AG, 2007.

41.3.5 Radio Frequency Welding

TPU (form: coated fabric)

The high frequency (27.12 MHz) weldability of a thermoplastic polyurethane elastomer coated fabric showed that maximum heating occurred at 50ºC (122°F). The highest peeling forces were found when the welding temperature exceeded that of the melting point (180°C; 356°F) of the hard segments in the polymer.

The interactions occurring during welding were found to depend on the temperature. At temperatures below 180ºC (356°F), the peeling resistance only derived from entanglements of flexible segments at the interface between the two TPU-coated fabrics. At temperatures of 180ºC (356°F) and above, the melting and mixing of hard segments produced total cohesion of the two coated fabrics, resulting in an enhanced peeling force.

Reference: Hollande S, Laurent JL, Lebey T: High-frequency welding of an industrial thermoplastic polyurethane elastomer-coated fabric. *Polymer*, 39(22), p. 5343, 1998.

TPAU (chemical type: aromatic polyurethane)

In this RF welding study, polyurethane bonded well to itself and all flexible and rigid PVCs. An interesting result was obtained when the method of bond rupture was considered. When polyurethane was welded to itself or rigid PVC, samples which were purposely cut through during welding produced better results. However, in polyurethane/flexible PVC combinations, samples welded without cutting through gave superior results (Table 41.4).

Heat ageing tended to decrease weld strength of polyurethane/polyurethane and polyurethane/flexible PVC combinations, whereas weld strength increased in the polyurethane/rigid PVC combination. It is felt that plasticizer migration from the flexible materials to the weld site may be compromising peel strength in the polyurethane/flexible PVC combination. This phenomenon is accelerated by elevated temperature ageing. Rigid PVC, however, lacks plasticizer and elevated temperature ageing may increase the chance of chain entanglement after welding.

Reference: Leighton J, Brantley T, Szabo E: RF welding of PVC and other thermoplastic compounds. ANTEC 1992, Conference proceedings, Society of Plastics Engineers, Detroit, May 1992.

41.3.6 Adhesive Bonding

Dow Chemical: Pellethane 2363-55D

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

Table 41.4. Radio Frequency Weld Strengths of Aromatic Polyester Polyurethane Between Itself and Other Materials*

Material	Joining Material	RF Welded Without Cutting Through Samples	Samples Purposely Cut Through During RF Welding	
			No ageing	Aged 48 hr at 60°C (140°F)
Aromatic polyester polyurethane	TPE alloy	No bond	No bond	
Aromatic polyester polyurethane	Styrenic TPE	No bond	No bond	
Aromatic polyester polyurethane	Aromatic polyester polyurethane	Fair (6–15% potential)	Excellent (31–50% potential)	Fair (6–15% potential)
Aromatic polyester polyurethane	Filled radiopaque PVC 75A	Excellent (31–50% potential)	Good (16–30% potential)	Fair (6–15% potential)
Aromatic polyester polyurethane	Clear rigid PVC 80D	Fair (6–15% potential)	Excellent (31–50% potential)	Superior (> 50% potential)
Aromatic polyester polyurethane	Clear flexible PVC 80A	Superior (>50% potential)	Good (16–30% potential)	Fair (6–15% potential)
Aromatic polyester polyurethane	Clear flexible PVC 65A	Excellent (31–50% potential)	Good (16–30% potential)	Fair (6–15% potential)

*The breaking strength per unit cross-sectional area of each weld was calculated, then divided by the tensile strength of the weaker material. This number (multiplied by 100) gave the weld strength expressed as a percentage of the highest possible value or "potential".

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches per second (0.25 mm/s).

While the bond strengths in Table 41.5 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 41.5, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in “real world” applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than just selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 instant adhesive, used in conjunction with Prism Primer 770, created bonds that were stronger than the substrate for most of

Table 41.5. Shear Strengths of Pellethane 2363-55 PU to PU Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[a]

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Unfilled resin (shore D)	14 rms	200 (1.4)	350 (2.4)	1400 (9.7)	350 (2.4)	350 (2.4)	1150 (7.9)
Roughened	167 rms	350 (2.4)	1350 (9.3)	1950 (13.5)	1300 (9.0)	1500 (10.3)	1700 (11.7)
UV stabilizer	1% Tinuvin 328	100 (0.7)	200 (1.4)	950 (6.6)	150 (1.0)	350 (2.4)	750 (5.2)
Flame retardant	15% BT-93; 2% Antimony Oxide	200 (1.4)	450 (3.1)	> 1850[b] (> 12.8)[b]	600 (4.1)	> 1400[b] (> 9.7)[b]	> 1350[b] (>9.3)[b]
Plasticizer	13% TP-95	50 (0.3)	150 (1.0)	> 750[b] (> 5.2)[b]	150 (1.0)	200 (1.4)	450 (3.1)
Lubricant #1	0.5% Mold Wiz INT-33PA	200 (1.4)	800 (5.5)	> 2150[b] (> 14.8)[b]	700 (4.8)	900 (6.2)	> 1800[b] (> 12.4)[b]
Lubricant #2	0.5% FS1235 Silicone	450 (3.1)	> 2250[b] (> 15.5)[b]	> 2900[b] (> 20.0)[b]	1250 (8.6)	> 2650[b] (> 18.3)[b]	> 2350[b] (> 16.2)[b]

[a] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and (MPa).

[b] Due to the severe deformation of the block shear specimens, testing was stopped before the actual bond strength achieved by the adhesive could be determined (the adhesive bond never failed).

the polyurethane formulations evaluated. Typically, most of the adhesives tested achieved good bond strengths. Loctite 3651 and Hysol 1942 hot melt adhesives achieved the lowest bond strengths on unfilled polyurethane.

Surface Treatments: The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, resulted in a large, statistically significant increase in the bond strengths achieved on polyurethane. Surface roughening also resulted in a statistically significant increase in the bond strengths achieved on polyurethane for all the adhesives evaluated.

Other Information: Polyurethane can be stress-cracked by uncured cyanoacrylate adhesives, so any excess adhesive should be removed from the surface immediately. Polyurethane is compatible with acrylic adhesives, but can be attacked by their activators before the adhesive has cured. Any excess activator should be removed from the surface immediately. Polyurethane is incompatible with anaerobic adhesives. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics*, *Vol. 4,* Supplier design guide, Loctite Corporation, 2006.

BASF: Elastollan

In order to facilitate bonding, it is recommended to use Elastollan grades without lubricant. Polyurethane-based elastic adhesives have proved successful in the bonding of Elastollan parts. Epoxy resin adhesives are used for bonding to metals and other hard materials.

Reference: *Elastollan Processing Recommendations*, Supplier technical information (Z/M, Fro 208-2-05/GB), BASF, 2005.

41.4 Styrenic Thermoplastic Elastomer

41.4.1 General

Evode Plastics: Evoprene G (chemical type: styrene ethylene butylene styrene block copolymer (SEBS))

Heat and ultrasonic welding operations can be carried out on molded and extruded parts, although bond strengths are not as high as those achieved with more polar materials.

Reference: *Technical Information Evoprene G*, Supplier technical report (RDS 028/9240), Evode Plastics.

41.4.2 Radio Frequency Welding

Styrenic TPE

Although initial radio frequency (RF) welds in styrenic thermoplastic elastomers appeared to be good, subsequent evaluation showed them to be of poor quality. In fact, the bonds were easily separated by hand. No useable welds were obtained for any combination with this material including bonding to itself. A possible explanation for this is the presence of aromatic groups on the polymer chains, resulting in steric hindrance. Consequently, it is difficult for these materials to become mobile and entangle without mechanical mixing.

Reference: Leighton J, Brantley T, Szabo E: RF welding of PVC and other thermoplastic compounds. ANTEC 1992, Conference proceedings, Society of Plastics Engineers, Detroit, May 1992.

41.4.3 Adhesive Bonding

Evode Plastics: Evoprene G (chemical type: styrene ethylene butylene styrene block copolymer (SEBS))

Special cyanoacrylate adhesives have been developed which are capable of giving good bond strengths between Evoprene G compounds and a variety of substrates (e.g., Evotech TC733 from Evode Speciality Adhesives). In addition, special primers are now being marketed, which allow assembly or insert bonding to take place with a range of adhesives.

Reference: *Technical Information Evoprene G*, Supplier technical report (RDS 028/9240), Evode Plastics.

41.5 Vinyl Thermoplastic Elastomer

41.5.1 Ultrasonic Welding

Plasticized PVC (form: artificial leather)

Artificial leather is a combination of natural or synthetic fibers with plasticized PVC films.

In contrast to other methods of welding artificial leather, ultrasound welding makes it possible to produce high quality welded joints even if the nonthermoplastic base and thermoplastic coatings are in contact. Ultrasound welding can be used successfully for welding artificial leather through a nonthermoplastic base with thermoplastic sheet or film substrates made of a material compatible with the material of the coating of artificial leather, and also in the presence of an intermediate layer, for example, made of foam polyurethane (FPU), between the layers of artificial leather or artificial leather and the substrates.

In joining artificial leather with the PVC substrate through the intermediate layer of FPU, at the moment of completion of filtration of the material of the PVC coating through the porous base and the formation of physical contact of the melt of the coating with the PVC substrate, the FPU is transferred into the viscous-fluid state, and is removed from the welding zone.

Ultrasound welding artificial leather produces welded joints with high strength properties and aesthetic external appearance, with the thickness of the welded joint restricted in the range 0.7–0.9 of the total thickness of the coating and the PVC substrate. Experimental results show that over a wide range of welding conditions, the shear strength is 0.8–0.9 and the delamination strength is 0.5–0.6 of tensile strength. In testing welded joints for delamination, failure took place by separation of the coating from the base.

Reference: Volkov SS: Ultrasound welding of components made from artificial leather. *Welding International*, 17(12), p. 999, 2003.

41.5.2 Radio Frequency Welding

PVC Polyol

Flexible PVC, in part because of its low glass transition temperature, readily bonds to other flexible PVCs, aromatic polyester polyurethane and rigid PVC. Bonding, however does not occur with styrenic TPEs or TPE alloys under the conditions used in this study. Several factors may account for this including steric hindrance, polarity, glass transition temperature and morphology differences. High levels of barium sulfate filler do not seem to be detrimental to flexible PVC weld strength. The effects of heat ageing appear to be minimal under the conditions studied. The method of bond rupture during testing was critical for flexible PVC. The samples welded without cutting through produced higher results than samples purposely cut through during welding (Table 41.6).

Reference: Leighton J, Brantley T, Szabo E: RF welding of PVC and other thermoplastic compound*s*. ANTEC 1992, Conference proceedings, Society of Plastics Engineers, Detroit, May 1992.

41.5.3 Solvent Welding

PVC Polyol (form: tubing)

In tests conducted to evaluate the bondability/ compatibility of plasticized PVC tubing to rigid, transparent thermoplastics, all of the materials tested, except polystyrene, exhibited the level of integrity which is characteristically required by the healthcare industry. With the proper selection of a solvent or solvent mixture, each material can consistently provide a strong bond which is easy to assemble, and shows no signs of crazing. Materials tested included acrylic (PMMA), glycol-modified polyethylene terephthalate (PETG), styrene acrylonitrile (SAN), rigid polyvinyl chloride (PVC), transparent acrylonitrile butadiene styrene (TABS), styrene-butadiene block copolymer (SB), polycarbonate (PC), glycol modified polycyclohexylenedimethylene terephthalate/ polycarbonate blend (PCTG/PC), rigid thermoplastic polyurethane (RTPU), and polystyrene (PS).

Reference: Haskell A: Bondability/compatibility of plasticized PVC to rigid, transparent thermoplastics. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

Alpha Chemical: PVC 2235L85

Figure 41.3 provides a representative sample of the bond strength that can be achieved with Lexan 1310 polycarbonate resin adhered to flexible PVC. Of the solvents, the methylene chloride/ cyclohexanone combination typically yielded the highest results when bonding Lexan resins to PVC.

Figure 41.4 provides a representative sample of the bond strength that can be achieved with Ultem 1000 polyetherimide resin adhered to flexible PVC. Of the solvents, the cyclohexanone appeared to withstand the greatest load before joint failure.

Reference: *Guide to Engineering Thermoplastics for the Medical Industry*, Supplier design guide (MED-114), General Electric Company.

41.5.4 Adhesive Bonding

Alpha Chemical: PVC 2235L85

The UV-curable adhesives tended to produce a strong bond joint between GE Plastics Lexan 1310 polycarbonate resin and flexible PVC, causing the PVC to yield before the adhesive. UV-curable adhesives also produced a good bond between GE Plastics Ultem 1000 PEI and flexible PVC. However, if UV-curable adhesives are used with Ultem resins, the UV light must be transmitted through the material it is bonded to, not the Ultem resin.

Reference: *Guide to Engineering Thermoplastics for the Medical Industry*, Supplier design guide (MED-114), General Electric Company.

Table 41.6. Radio Frequency Weld Strengths of Flexible Polyvinyl Chloride (PVC) Between Itself and Other Materials*

Material	Joining Material	RF Welded Without Cutting Through Samples	Samples Purposely Cut Through During RF Welding		Change in Weld Strength After Exposure to 5–5.5 Mrads of Gamma Radiation
			No Ageing	Aged 48 hrs at 60°C (140°F)	
Clear flexible PVC 65A	TPE alloy	No bond	No bond		
Clear flexbile PVC 65A	Styrenic TPE	No bond	No bond		
Clear flexbile PVC 65A	Aromatic polyester polyurethane	Excellent (31–50% potential)	Good (16–30% potential)	Fair (6–15% potential)	
Clear flexbile PVC 65A	Filled radiopaque PVC 75A	Superior (>50% potential)	Fair (6–15% potential)	Good (16–30% potential)	
Clear flexbile PVC 65A	Clear rigid PVC 80D	Fair (6–15% potential)	Excellent (31–50% potential)	Excellent (31–50% potential)	0% potential
Clear flexbile PVC 65A	Clear flexible PVC 80A	Superior (>50% potential)	Good (16–30% potential)	Good (16–30% potential)	
Clear flexbile PVC 65A	Clear flexible PVC 65A	Good (16–30% potential)	Good (16–30% potential)	Good (16–30% potential)	+1% potential
Clear flexible PVC 80A	TPE alloy	No bond	No bond		
Clear flexible PVC 80A	Styrenic TPE	No bond	No bond		
Clear flexible PVC 80A	Aromatic polyester polyurethane	Superior (>50% potential)	Good (16–30% potential)	Fair (6–15% potential)	
Clear flexible PVC 80A	Filled radiopaque PVC 75A	Excellent (31–50% potential)	Good (16–30% potential)	Good (16–30% potential)	
Clear flexible PVC 80A	Clear rigid PVC 80D	Excellent (31–50% potential)	Good (16–30% potential)	Superior (>50% potential)	+3% potential
Clear flexible PVC 80A	Clear flexible PVC 80A	Superior (>50% potential)	Good (16–30% potential)	Good (16–30% potential)	+5% potential
Filled radiopaque PVC 75A	TPE alloy	No bond	No bond		
Filled radiopaque PVC 75A	Styrenic TPE	No bond	No bond		
Filled radiopaque PVC 75A	Aromatic polyester polyurethane	Excellent (31–50% potential)	Good (16–30% potential)	Fair (6–15% potential)	
Filled radiopaque PVC 75A	Filled radiopaque PVC 75A	Excellent (31–50% potential)	Good (16–30% potential)	Good (16–30% potential)	

*The breaking strength per unit cross-sectional area of each weld was calculated, then divided by the tensile strength of the weaker material. This number (multiplied by 100) gave the weld strength expressed as a percentage of the highest possible value or “potential”.

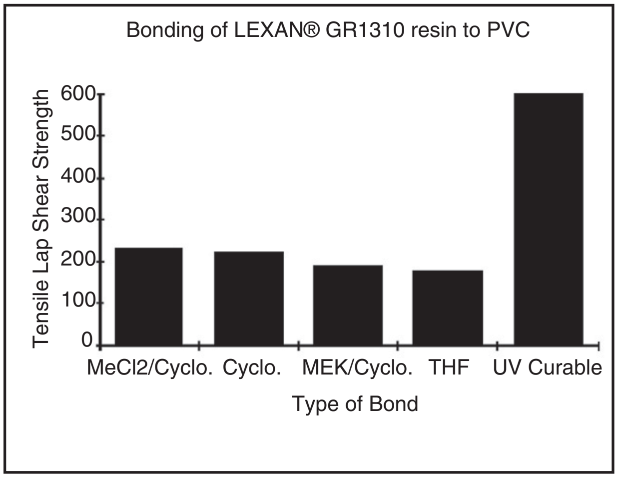


Figure 41.3. Adhesive and solvent bond strengths of Lexan 1310 polycarbonate resin adhered to Alpha Chemical PVC 2235L85 flexible polyvinyl chloride (PVC). (Solvents: MeCl2: methylene chloride; MEK: methyl ethyl ketone; cyclo: cyclohexanone; THF: tetrahydrofuran. Note: solvent combinations are 50:50 solutions).

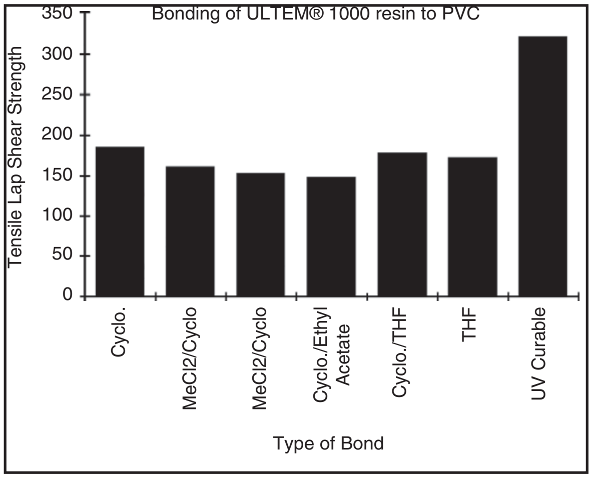


Figure 41.4. Adhesive and solvent bond strengths of Ultem 1000 polyetherimide resin adhered to Alpha Chemical PVC 2235L85 flexible PVC. (Solvents: $MeCl_2$: methylene chloride; MEK: methyl ethyl ketone; cyclo: cyclohexanone; THF: tetrahydrofuran. Note: solvent combinations are 50:50 solutions).

41.6 Elastomeric Alloys

41.6.1 General

DSM: Sarlink 3000

Sarlink 3000 grades can be thermally welded to themselves or to other nonpolar polymers such as polyolefins.

Reference: *Sarlink Thermoplastic Elastomers*, Supplier technical report, DSM Thermoplastic Elastomers.

41.6.2 Heated Tool Welding

EPDM/PP blend (features: cross-linked EPDM phase)

In this study, the heated tool temperature was varied between 200 and 240ºC (392–464°F), the heating time was varied between 10 and 40 seconds, and the joining pressure was varied between 0.05 MPa (7 psi) and 0.2 MPa (29 psi). The short-term welding factors reached values up to 86%. The maximum yield strain of the weld was 69% of the base material value.

Reference: Tüchert C, Bonten C, Schmachtenberg E: Welding of a thermoplastic elastomer. ANTEC 2001, Conference proceedings, Society of Plastics Engineers, Dallas, May 2001.

ExxonMobil Chemical: Santoprene

The Teflon-coated platen should be about 200–260ºC (400–500ºF). The tensile strength of a Santoprene TPV thermal weld is typically 50–70% of the original value.

Reference: *Welding Santoprene Thermoplastic Vulcanizate*, Supplier technical guide (TCD01401), ExxonMobil Chemical, 2001.

41.6.3 Ultrasonic Welding

ExxonMobil Chemical: Santoprene

A lap shear joint between 3 mm (0.115 inch) thick Santoprene TPV sheets was spot welded using a 76 × 25 mm (3 × 1 inch) rectangular horn with a 1600 W power supply and a 1.5 booster. Weld time was 2.0 seconds and the hold time was 1.5 seconds. Air pressure at 0.3 MPa (40 psi) was used to produce contact pressure.

With a 6 mm (1/4 inch) cylindrical horn, a 5.3 kN/m shear strength could be attained at a spot weld using Santoprene TPV 101–80 and 203–40. The energy was applied through a horn embedded into the harder layer.

Intense energy input and a longer contact time are required to impart sufficient heat at a distance from the horn. Before the interface heats sufficiently, the Santoprene TPV in contact with the horn overheats and begins to degrade. Furthermore, a small horn will begin to recede into the Santoprene TPV substrate, leaving an indentation. However, this is the only way the horn can be brought close enough to the interface to induce melting in the opposite substrate.

Ultrasonic welding of hard Santoprene TPV is marginal; with soft grades it should not be recommended. Grade 87A and harder can be effectively bonded to polypropylene by ultrasonic welding.

Reference: *Welding Santoprene Thermoplastic Vulcanizate*, Supplier technical guide (TCD01401), ExxonMobil Chemical, 2001.

41.6.4 Vibration Welding

ExxonMobil Chemical: Santoprene

Santoprene TPV 201-73 could not be vibration welded, probably because its low modulus made clamping difficult. The part flexed in the joint area, so that relative motion could not be obtained. Santoprene TPV 203-40, on the other hand, welds very well. A lap shear joint exhibited a tensile strength of the order of 9.0 MPa (1300 psi), with failure occurring at the edge of the joint.

Reference: *Welding Santoprene Thermoplastic Vulcanizate*, Supplier technical guide (TCD01401), ExxonMobil Chemical, 2001.

41.6.5 Radio Frequency Welding

Advanced Elastomer Systems: EPDM/PP blend
(features: cross-linked EPDM phase: form: extruded sheet)

Catalytic RF welding technology was studied to characterize the weldability of a range of TPVs (thermoplastic vulcanizates).

The results showed that TPVs can be successfully welded by this method. The rubber versus plastic ratio of the TPV material has a bearing on the weldability and level of weld strength, due to the percentage of weldable plastic phase available.

Reference: Raulie R, Smith D: Radio frequency welding of thermoplastic vulcanizates. ANTEC 2005, Conference proceedings, Society of Plastics Engineers, Boston, May 2005.

ExxonMobil Chemical: Santoprene

Geolast TPV may be RF welded. However, because of its lower polarity, it requires higher energy than most polar materials. Geolast TPV 703-40 requires 5–8 seconds at 2.0–2.5 amps for bonding. RF welding is being employed to bond Geolast TPV tank liners. Santoprene TPV and Vyram TPV do not RF weld as a result of their nonpolar character.

Reference: *Welding Santoprene Thermoplastic Vulcanizate*, Supplier technical guide (TCD01401), ExxonMobil Chemical, 2001.

TPE Alloys

As with styrenic TPE, no practical RF welds were obtained with any arrangement of polymer groups in TPE alloys. This is attributed to the same steric hindrance as with styrenic TPE.

Reference: Leighton J, Brantley T, Szabo E: RF welding of PVC and other thermoplastic compounds. ANTEC 1992, Conference proceedings, Society of Plastics Engineers, Detroit, May 1992.

41.6.6 Hot Gas Welding

ExxonMobil Chemical: Santoprene

For low speed operation, temperatures of 200–260°C (400–500°F) will melt the surface. Air and nitrogen produced the same results in laboratory studies.

Reference: *Welding Santoprene Thermoplastic Vulcanizate*, Supplier technical guide (TCD01401), ExxonMobil Chemical, 2001.

41.6.7 Induction Welding

ExxonMobil Chemical: Santoprene

EMA Bond: Both peel and lap shear configurations of Santoprene TPV 201-73 could be bonded with a polypropylene-based EMA weld material in 2.5 seconds using a 2 kW generator. Peel bonds were nonuniform and tore in the Santoprene TPV at 2.6 to 4.0 kN/m. Failure was by tearing the Santoprene TPV substrate. Lap shear strength was in excess of 3.4 MPa (500 psi).

Hellerbond: Rubber tear of 5.3–14.0 kN/m can routinely be produced in Santoprene TPV joints inductively bonded with ferrite-filled Santoprene TPV or polypropylene in 1.5 seconds. The Hellerbond process appears to be more suitable for Santoprene TPV applications.

Reference: *Welding Santoprene Thermoplastic Vulcanizate*, Supplier technical guide (TCD01401), ExxonMobil Chemical, 2001.

41.6.8 Adhesive Bonding

ExxonMobil Chemical: Santoprene

Recent work has shown that it is possible to increase the surface energy of Santoprene TPV (Shore 35A to 50D) using standard corona or flame pretreatment processes. The target should be to generate a minimum surface energy of 40 mN/m. It is possible to achieve this by careful control of the process parameters of the pretreatment equipment. It should be noted that the pretreatment process may need to be used in conjunction with a suitable primer system to achieve the desired level of adhesion performance in the final component.

Bonding with Cyanoacrylates: Using cyanoacrylates as assembly adhesives produces a strong rigid shear bond. However, the adhesive layer is susceptible to failure if exposed to flexure, vibration, and moisture. Loctite markets a polyolefinic primer, Loctite 770, which is suitable for use with Santoprene TPV.

Primer baking must be avoided due to a nonchlorinated PP chemistry of the primer. Always put the cyanoacrylate adhesive on the substrate, never onto the primer-coated Santoprene TPV surface. Bonded parts need a minimum of two minutes setting time under full pressure. Full bond strength develops over 24 hours.

Bonding with Double-coated Tapes: The use of double-coated tapes for assembly bonding is a very easy and clean operation. Good shear strengths and, depending on the tape choice, reasonable peel strengths can be achieved. Priming of the Santoprene TPV surface is necessary in all cases; baking of the primer is optional. If baking is carried out, lamination to the pre-primed Santoprene TPV surface should be done while still warm.

Suggested combinations are Chemosil X8532 (Henkel) or Thixon (Rohm and Haas) primers in combination with 3M tapes, 5361 or 4205, or Fastape 2493 from Avery-Dennison.

Bonding with Epoxy: At present, there are no Santoprene TPV specific primers available. Primers used for painting Santoprene TPV can however be modified to give good bonding to epoxies. This is achieved by adding 1% by weight of the epoxy-hardener to the primer, providing the products are compatible.

Baking of the primer is highly recommended in order to maximize the bond strength. The warm Santoprene TPV surface can be directly bonded to the other substrate with the epoxy adhesive. The increased temperature reduces the time for full adhesive cure. It is recommended to keep the assembly under constant pressure until the epoxy adhesive has fully reacted. This process can also be done at elevated temperature to avoid the extra baking step.

A Henkel product, Metallon 2108, has been found to be a good performance epoxy adhesive for the flexible Santoprene TPV surfaces.

Bonding with Hot Melts: A primer is required to achieve a bond between the hot melt and the Santoprene TPV surface. Henkel primer Chemosil X8533 and Rohm and Haas primer Thixon X9279 can be used for coating the Santoprene TPV surface. Baking of the primer is optional as the hot melts are applied at a typical applicator temperature of 180ºC (356ºF). There is often enough heat energy from the hot melt to bake the primer to the Santoprene TPV surface. A major drawback of hot melts is their low softening point, which reduces their applicability to Santoprene TPV parts with a maximum operating temperature of 70ºC (158ºF).

Bonding with Polyurethanes (PUs) or Acrylic Solutions: PU adhesives give reasonable bond strength to Santoprene TPV, provided the primer is baked. Suitable primers are Henkel's Chemosil X8533 or Rohm and Haas' Thixon X9279. Primers used for painting may give good results, depending on their compatibility to PU adhesives.

Adhesives from Rubber Solutions: Adhesives based on rubber solutions of typically natural rubber, polychloroprene, or nitrile rubber will not bond to Santoprene TPV without using a suitable primer. Recommended primers are Henkel Chemosil X8533 or Rohm and Haas Thixon X9279. Baking is again mandatory to create strong joints.

Reference: *Assembly Bonding of Santoprene Thermoplastic Vulcanizate*, Supplier technical guide (TCD00901), ExxonMobil Chemical, 2001.

DSM: Sarlink 3000

Adhesive bonding of polymeric materials is affected by the polarity and compatibility of the materials. Highly polar substances tend to bond better than those that have low polarity. Good adhesion can be obtained with Sarlink 3000, particularly with solvent based systems at elevated temperatures.

Reference: *Sarlink Thermoplastic Elastomers*, Supplier technical report, DSM Thermoplastic Elastomers.

42.1 Diallyl Phthalate Polymer

42.1.1 Adhesive Bonding

Rogers: DAP

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches/second (0.25 mm/s).

While the bond strengths in Table 42.1 give a good indication of the typical bond strengths that can be achieved as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and

Table 42.1. Shear Strengths of DAP to DAP Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[b]

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Grade RX3-1-525F	Short glass-fiber reinforced flame retardant black coloring—18 rms	>1950[a] (>13.5)[a]	>3150[a] (>21.7)[a]	150 (1.0)	>2700[a] (>18.6)[a]	350 (2.4)	350 (2.4)
Grade RX3-1-525F roughened	28 rms	>1950[a] (>13.5)[a]	>3150[a] (>21.7)[a]	300 (2.1)	>2700[a] (>18.6)[a]	1400 (9.7)	350 (2.4)
Grade RX1310	Short glass-fiber reinforced green coloring—16 rms	>1700[a] (>11.7)[a]	>2350[a] (>16.2)[a]	150 (1.0)	>3000[a] (>20.7)[a]	650 (4.5)	450 (3.1)
Grade RX1310 roughened	27 rms	>1700[a] (>11.7)[a]	>2350[a] (>16.2)[a]	550 (3.8)	>3000[a] (>20.7)[a]	2150 (14.8)	1450 (10.0)
Grade RX1-510N	Mineral-filled blue coloring 14 rms	>1700[a] (>11.7)[a]	>2900[a] (>20.0)[a]	100 (0.7)	>2750[a] (>19.0)[a]	500 (3.5)	300 (2.1)
Grade RX1-510N roughened	24 rms	>2550[a] (>17.6)[a]	>2900[a] (>20.0)[a]	1050 (7.2)	>2750[a] (>19.0)[a]	2300 (15.9)	1700 (11.7)

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

fillers were tested individually in Table 42.1, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: The five cyanoacrylates tested, namely Prism 401, Prism 4011, Super Bonder 414, and Black Max 380 instant adhesives, and Flashcure 4305 light cure adhesive, created bonds that were stronger than the three grades of DAP evaluated. Most of the other adhesives evaluated showed fair to excellent bond strengths on DAP. There were no statistically significant differences between the bondability of the three grades of DAP evaluated.

Surface Treatments: The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, significantly lowered the bond strengths achieved on DAP. Surface roughening caused a statistically significant increase in bond strength when using Depend 330 and Loctite 3105 and 3311 light cure adhesives. The effect of surface roughening on the bond strengths achieved by cyanoacrylate adhesives could not be determined because both roughened and unroughened DAP bonded with cyanoacrylates resulted in substrate failure.

Other Information: Allylic esters are compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

42.2 Epoxy

42.2.1 Adhesive Bonding

Epoxy

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches/second (0.25 mm/s).

While the bond strengths in Table 42.2 give a good indication of the typical bond strengths that can be achieved as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 42.2, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive

Table 42.2. Shear Strengths of Epoxy to Epoxy Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[b]

Material Composition		Loctite adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive, General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Westinghouse G-10 Epoxyglass	21 rms	3200 (22.1)	3350 (23.1)	250 (1.7)	3600 (24.8)	1000 (6.9)	1500 (10.3)
Westinghouse G-10 roughened	33 rms	3200 (22.1)	2150 (14.8)	1500 (10.3)	1800 (12.4)	1700 (11.7)	1500 (10.3)
Loctite Fixmaster Poxy Pak	92 rms	2100 (14.5)	>3200[a] (>22.1)[a]	2850 (19.7)	2650 (18.3)	1000 (6.9)	1550 (10.7)
Loctite Fixmaster Poxy Pak roughened	167 rms	3750 (25.9)	>3200[a] (>22.1)[a]	>2650[a] (>18.3)[a]	>3750[a] (>25.9)[a]	>1600[a] (>11.0)[a]	1550 (10.7)
Loctite Fixmaster fast cure epoxy	116 rms	1600 (11.0)	1500 (10.3)	2100 (14.5)	2750 (19.0)	1350 (9.3)	1250 (8.6)
Loctite Fixmaster fast cure epoxy roughened	134 rms	>1850[a] (>12.8)[a]	>1900[a] (>13.1)[a]	>1700[a] (>11.7)[a]	>1900[a] (>13.1)[a]	>1200[a] (>8.3)[a]	2050 (14.1)

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Flashcure 4305 light cure adhesive and Hysol E-30CL epoxy adhesive both achieved bond strengths that were stronger than the grade of epoxy tested. The other cyanoacrylate adhesives evaluated (Black Max 380, Prism 401 and Super Bonder 414) achieved the highest bond strengths on the various types of epoxies tested.

Surface Treatments: Surface roughening usually caused either no effect or a statistically significant increase in the bond strengths achieved on epoxy. The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused a significant decrease in the bond strengths achieved for most of the epoxies evaluated.

Other Information: Epoxy is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

42.3 Phenolic

42.3.1 Adhesive Bonding

Occidental: Durez

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches/second (0.25 mm/s).

While the bond strengths in Table 42.3 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 42.3, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the mag-

Table 42.3. Shear Strengths of Durez Phenolic to Phenolic Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[b]

Material Composition		**Loctite Adhesive**					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
General-purpose 25000118	Cellulose, wood flour, zinc stearate, and calcium stearate filled with black pigment	1600 (11.0)	600 (4.1)	150 (1.0)	400 (2.8)	900 (6.2)	1100 (7.6)
25000118 roughened		1600 (11.0)	600 (4.1)	150 (1.0)	400 (2.8)	900 (6.2)	1450 (10.0)
Glass-filled 32245	Mineral filled in addition to general-purpose ingredients	1500 (10.3)	450 (3.1)	150 (1.0)	250 (1.7)	850 (5.9)	600 (4.1)
Heat-resistant 152118	Mineral filled in addition to general-purpose ingredients	>1750[a] (>12.1)[a]	1800 (12.4)	100 (0.7)	1800 (12.4)	500 (3.5)	1250 (8.6)
Electric grade 156122	Glass, mineral filled in addition to general-purpose ingredients	>1650[a] (>11.4)[a]	400 (2.8)	150 (1.0)	400 (2.8)	600 (4.1)	1050 (7.2)
Plenco 04300	Mineral-filled, heat-resistant courtesy of Plastics Engineering Company	>1900[a] (>13.1)[a]	>1750[a] (>12.1)[a]	50 (0.3)	>2300[a] (>15.9)[a]	>1800[a] (>12.4)[a]	750 (5.2)

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

nitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Hysol E-30CL epoxy adhesive and Fixmaster high performance epoxy both achieved bond strengths that were higher than the grade of unfilled phenolic tested. Black Max 380 instant adhesive, Flashcure 3105 and 4305 light cure adhesives, Speedbonder H3000 structural adhesive, Loctite 3030 adhesive, Hysol E-00CL, E-90FL and E-20HP epoxy adhesives, and Hysol 3631 hot melt adhesive all achieved the highest bond that did not result in substrate failure. Super Bonder 414 instant adhesive, Depend 330 adhesive, Speedbonder H4500 structural adhesive, Hysol E-214HP epoxy adhesive, and Hysol U-05FL urethane adhesive typically achieved lower, but still significant bond strengths.

Surface Treatments: The use of Prism primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused a statistically significant decrease in the bondability of the various grades of phenolic that were evaluated. Surface roughening caused a statistically significant increase in the bond strengths achieved on phenolics when using Loctite 3105 and 3311 light cure adhesives, but had no significant effect when using any of the other adhesives.

Other Information: Phenolic is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

42.4 Polyester

42.4.1 Adhesive Bonding

Thermoset Polyester

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3 M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches/second (0.25 mm/s).

While the bond strengths in Table 42.4 give a good indication of the typical bond strengths that can be achieved, as well as the effect of many fillers and additives, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material. In addition, the additives and fillers were tested individually in Table 42.4, so the effect of interactions between these different fillers and additives on the bondability of materials could not be gauged.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Adhesive Performance: Prism 401 and Super Bonder 414, both cyanoacrylate adhesives, Black Max 380, a rubber toughened cyanoacrylate adhesive, Flashcure 4305 light cure adhesive, Hysol E-20HP epoxy

Table 42.4. Shear Strengths of Thermoset Polyester to Thermoset Polyester Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[b]

Material Composition		**Loctite adhesive**					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
C-685 Black 183	20-30% glass fiber mineral filled; 15 rms	>1350[a] (>9.3)[a]	>1350[a] (>9.3)[a]	350 (2.4)	>1900[a] (>13.1)[a]	700 (4.8)	600 (4.1)
C-685 Roughened	33 rms; Cyglas courtesy of American Cyanamid	>900[a] (>6.2)[a]	1200 (8.3)	650 (4.5)	800 (5.5)	700 (4.8)	1650 (11.3)
Dielectrite 48-53-E	courtesy of Industrial Dielectrics	>1400[a] (>9.7)[a]	>1400[a] (>9.7)[a]	>600[a] (>4.1)[a]	>1300[a] (>9.0)[a]	450 (3.1)	1100 (7.6)
Dielectrite 44-10	Unspecified glass fill; courtesy of Industrial Dielectrics	>1450[a] (>10.0)[a]	>1300[a] (>9.0)[a]	350 (2.4)	>1350[a] (>9.3)[a]	650 (4.5)	1150 (7.9)
Dielectrite 46-16-26	Unspecified glass fill; courtesy of Industrial Dielectrics	>2100[a] (>14.5)[a]	>2050[a] (>14.1)[a]	450 (3.1)	>1950[a] (>13.5)[a]	600 (4.1)	1000 (6.9)
Dielectrite 46-3	Unspecified glass fill; courtesy of Industrial Dielectrics	>1600[a] (>11.0)[a]	>1550[a] (>10.7)[a]	250 (1.7)	>1250[a] (>8.6)[a]	700 (4.8)	650 (4.5)

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses)

adhesive and Fixmaster high performance epoxy achieved the highest bond strengths on the thermoset polyester, typically achieving substrate failure. With the exception of the hot melt adhesives and 3340 light cure adhesive, all other adhesives developed moderate to good bond strength on unfilled thermoset polyesters.

Surface Treatments: The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, are not recommended as they significantly decreased the bond strengths achieved on the grades of thermoset polyester that were evaluated. Surface roughening caused either no effect or a statistically significant increase in the bond strengths achieved by the acrylic adhesives. However, surface roughening typically resulted in a statistically significant increase in the bond strengths achieved by cyanoacrylate adhesives.

Other Information: Thermoset polyester is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol, Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.

42.5 Polyimide

42.5.1 General

Rhone Poulenc: Kinel

Kinel formulae cannot be welded because they are thermosets.

Reference: *Kinel Polyimide Compounds—Part Design, Processing*, Supplier design guide (ST/AN/0187/008), Rhone Poulenc.

42.5.2 Adhesive Bonding

Rhone Poulenc: Kinel

Articles made of Kinel can be assembled with the following adhesives, most of which are epoxy. These references are given as examples. Their resistance to high temperatures should however be checked according to the application:

Adhesive	Use Temperature
Loctite 620	240°C (464°F)
Loctitie 648	175°C (347°F)
Eccobond 104 (Emerson & Cummings)	290°C (554°F)
Eccobond 45 and Catalyst 15	190°C (374°F)

Reference: *Kinel Polyimide Compounds—Part Design, Processing*, Supplier design guide (ST/AN/0187/008), Rhone Poulenc.

42.5.3 Mechanical Fastening

Rhone Poulenc: Kinel

Screw flights should not be too fine—pitch (P) ≥ 1 mm (0.04 inches); they can be tapered (S1) or round with a pitch of 2.5–4 mm (0.10–0.16 inches). The flight should begin below the edge and end a distance of P/2 above the base.

Metal inserts cause no problems with Kinel 5514–5504, 3515, and 4525. They can be pressed in after molding (self-drilling) or be molded in. The latter is preferable.

Example: ring with a knurled steel insert diameter of 35 mm (1.4 inches):

	Extraction Torque
Molded in	>500 Nm
0.2 mm (0.008 inch) compression on diameter	300–350 Nm
0.3–0.5 mm (0.01–0.02 inch) compression on diameter	500 Nm

Self-drilling or self-tapping inserts must be strong enough to withstand distortion (e.g., warping of the inside thread) when they are inserted into the Kinel, which is very hard. Brass and light alloys should not be used. Steel is preferable.

Example: For a self-tapping screw diameter of 4.75 mm (0.19 inches) (thread root diameter of 3.3 mm (0.13 inches)), a preliminary hole diameter of 4.4 mm (0.17 inches) must be drilled, otherwise the plastic will chip.

Molded-in inserts can be anchored in the plastic by means of:

- Diagonal knurling
- Lengthwise knurling and hexagonal or square graining
- Radial holes around the edge

Inserts should have a cylindrical shoulder to hold them in the mold and withstand the force of the plastic flow.

Riveting: Riveting is possible, but riveting conditions must be adapted to the Kinel formula used.

Reference: *Kinel Polyimide Compounds—Part Design, Processing*, Supplier design guide (ST/AN/0187/008), Rhone Poulenc.

42.6 Polyurethane

42.6.1 Adhesive Bonding

Rimnetics: Rimnetics

For bonding RIM polyurethane parts, epoxy, or cyanoacrylate adhesives work well. The bonding area of a lap joint should be roughly three times the wall thickness.

Reference: *Rimnetics Part Design Guide—Polyurethane Products*, Supplier design guide, Rimnetics, Inc., 2007

Recticel: Colo-Fast LM 161 (chemical type: aliphatic polyurethane; features: low modulus elastomer)

Good adhesion to glass is exhibited by Colo-Fast LM161 with commercially used adhesion promoters (Table 42.5). 180° peel values are typically over 25 lbf (111 N), higher than required by automotive specifications. This adhesion is retained over a wide range of temperatures and after lengthy ageing under heat and humid conditions.

Reference: Carver TG, Kubizne PJ, Huys D: Reaction injection molded modular window gaskets using light stable aliphatic polyurethane. Polyurethanes: Exploring New Horizons. Proceedings of the SPI 30th annual technical/marketing conference, Conference proceedings, Society of the Plastics Industry, Toronto, Canada, October 1986.

42.7 Silicone

42.7.1 Adhesive Bonding

PDMS

The effect of UV/ozone pretreatment of polydimethylsiloxane (PDMS) on its adhesion to Loctite 3105 UV curable adhesive was evaluated using X-ray photoelectron spectroscopy.

Table 42.5. Adhesion of Colo-Fast LM 161 Polyurethane Reaction Injection Molding System to Glass With and Without Ageing

Adhesion Promoter	Ageing Condition	Glass*	Frit*
Lord (Chemlok AP-134)	None	29.2 (130)	25.7 (114)
Essex (2-part)	None	29.5 (131)	32.9 (146)
Lord (Chemlok AP-134)	After 1000 h at 88°C (190°F)	25.7 (114)	27.7 (123)
	After 1000 h at 38°C (100°F) and 100% RH	28.9 (129)	29.1 (129)
	After 1000 h water immersion at 32°C (90°F)	25.1 (112)	22.9 (102)

*180° peel values in lbf (N)

Developing adhesion between the PDMS and the adhesive proved to be the most difficult step. It was found that by using UV-pretreatment of the PDMS surface, the adhesion could be increased dramatically. This could be concluded from XPS data because the delaminated PDMS resembled the adhesive chemistry when substantial pretreatment times were used, indicating that delamination had occurred cohesively in the adhesive, not at the interface. Pretreatment times of as little as a few minutes could be used to obtain enhanced adhesion, but these generally required precisely controlled pretreatment and curing times. Longer pretreatment times, such as 18 minutes, allowed improved adhesion over a broader range of cure times.

Reference: Miller P, Gengenbach T, Sbarski I, Spurling T: XPS analysis of UV curable adhesive and its adhesion to PDMS. ANTEC 2005, Conference proceedings, Society of Plastics Engineers, Boston, May 2005.

Silicone

Silicone can be adhesively bonded by priming with Permabond POP primer, and using a cyanoacrylate adhesive.

Reference: *The Engineers Guide to Adhesives*, Supplier design guide, Permabond Engineering Adhesives.

42.8 Vinyl Ester

42.8.1 Adhesive Bonding

Vinyl Ester

A study was conducted to determine the bond strength of a representative matrix of plastics and the adhesives best suited to them. The block-shear (ASTM D 4501) test was used because it places the load on a thicker section of the test specimen; the specimen can therefore withstand higher loads before experiencing substrate failure. In addition, due to the geometry of the test specimens and the block shear fixture, peel and cleavage forces in the joint are minimized.

The substrates were cut into 1" × 1" × 0.125" (25.4 × 25.4 × 3.175 mm) block shear test specimens. All bonding surfaces were cleaned with isopropyl alcohol. The test specimens were manually abraded using a 3M heavy-duty stripping pad. The surface roughness was determined using a Surfanalyzer 4000 with a traverse distance of 0.03 inches (0.76 mm) and a traverse speed of 0.01 inches/second (0.25 mm/s).

While the bond strengths in Table 42.6 give a good indication of the typical bond strengths that can be achieved, they also face several limitations. For example, while the additives and fillers were selected because they were believed to be representative of the most commonly used additives and fillers, there are many types of each additive and filler produced by many different companies, and different types of the same additive or filler may not have the same effect on the bondability of a material.

Another consideration that must be kept in mind when using this data to select an adhesive/plastic combination is how well the block shear test method will reflect the stresses that an adhesively bonded joint will see in "real world" applications. Adhesively bonded joints are designed to maximize tensile and compressive stresses, and to minimize peel and cleavage stresses, so the magnitude of the former two are generally much larger than the latter two. Thus, the shear strength of an adhesive is generally most critical to adhesive joint performance, but since all joints experience some peel and cleavage stresses, their effects should not be disregarded.

Finally, selecting the best adhesive for a given application involves more than selecting the adhesive that provides the highest bond strength. Other factors such as speed of cure, environmental resistance, thermal resistance, suitability for automation, and price will play a large role in determining the optimum adhesive system for a given application.

Table 42.6. Shear Strengths of Derakane Vinyl Ester to Vinyl Ester Adhesive Bonds Made Using Adhesives Available from Loctite Corporation[b]

Material Composition		Loctite Adhesive					
		Black Max 380 (Instant Adhesive, Rubber Toughened)	**Prism 401** (Instant Adhesive, Surface Insensitive)	**Prism 401/ Prism Primer 770**	**Super Bonder 414** (Instant Adhesive General Purpose)	**Depend 330** (Two-Part, No-Mix Acrylic)	**Loctite 3105** (Light Cure Adhesive)
Derakane 411-45	Vinyl Ester resin with C-glass veil - 15 rms	950 (6.6)	1900 (13.1)	800 (5.5)	1950 (13.5)	400 (2.8)	1950 (13.5)
411-45 roughened	Vinyl Ester resin with C-glass veil - 27 rms	1950 (13.5)	1900 (13.1)	800 (5.5)	1950 (13.5)	1000 (6.9)	1950 (13.5)
Derakane 470-36	High Temperature/Corrosion Resistant Grade with C-glass veil	550 (3.8)	>2200[a] (>15.2)[a]	650 (4.5)	>2450[a] (>16.9)[a]	350 (2.4)	1500 (10.3)

[a] The force applied to the test specimens exceeded the strength of the material resulting in substrate failure before the actual bond strength achieved by the adhesive could be determined.

[b] All testing was done according to the block shear method (ASTM D4501). Values are given in psi and MPa (within parentheses).

Adhesive Performance: Flashcure 4305 light cure adhesive, Hysol E-90FL, E-30CL and E-20HP epoxy adhesives, Hysol U-05FL urethane adhesive, Hysol 3631 hot melt adhesive and Fixmaster high performance epoxy all achieved bond strengths that were greater than the grade of vinyl ester tested. The overall bondability of vinyl ester is good to excellent. The exceptions are the Hysol 3651, 7804 and 1942 hot melt adhesives, and 5900 flange sealant.

Surface Treatments: Surface roughening caused either no effect, or a statistically significant increase in the bond strengths achieved on vinyl ester. The use of Prism Primer 770, in conjunction with Prism 401 instant adhesive, or Prism 4011 medical device instant adhesive with Prism Primer 7701, caused a statistically significant decrease in the bondability of all the grades of vinyl ester that were evaluated.

Other Information: Vinyl ester is compatible with all Loctite adhesives, sealants, primers, and activators. Recommended surface cleaners are isopropyl alcohol and Loctite ODC Free Cleaner & Degreaser.

Reference: *The Loctite Design Guide for Bonding Plastics, Vol. 4*, Supplier design guide, Loctite Corporation, 2006.Reference: *Kinel Polyimide Compounds—Part Design, Processing*, Supplier design guide (ST/AN/0187/008), Rhone Poulenc.

43 Rubbers

43.1 Ethylene Propylene Rubber

43.1.1 Hot Gas Welding

ICI: EPDM

Results of this study indicated that satisfactory welds could not be achieved. With hot gas welding, the contractions that occur as the welds cool cannot be countered by maintaining pressure on the weld via the surrounding material, as is the case in many other plastics-welding techniques. Hence contraction cavities and incomplete fusion at the joints are likely. The results are that welded sheets have low ductility and reduced strength, though the strength reduction is not great if optimum welding conditions are used.

The optimum air temperature for ethylene propylene diene was determined to be 330°C (626°F). The speed of travel of the welding gun and the pressure applied are determined by the operator who will be constantly adjusting these parameters to achieve a weld of satisfactory appearance. The appearance of the weld is a good guide to its quality: the smoothness of the profile and the nature of the wash are features deserving particular attention. The ratio of weld strength (tensile) to that of the parent material was 0.78 using a single V butt weld and 0.67 using a double V butt weld.

Reference: Turner BE, Atkinson JR: Repairability of plastic automobile bumpers by hot gas welding. ANTEC 1989, Conference proceedings, Society of Plastics Engineers, New York, May 1989.

43.1.2 Laser Welding

EPDM (features: black, 3.17 mm (0.125 inch) thick plaque)

Contour laser welding has been carried out on EPDM welded to PP containing glass fiber filler, using a diode laser of wavelength 940 nm. The beam area was 11 mm^2 (0.017 inches^2), the laser power was varied from 60 to 150 W and the scanning speed was varied from 400 to 2500 mm/min (1.3–8.2 ft/min), giving line energies of 3.5–22.5 J/mm. Shear lap tensile samples were made with PP being the transmitting part and black EPDM being the absorbing part. The clamping pressure, defined as the clamping force divided by the overlap area was varied from 0.5 to 4.0 MPa (73–580 psi).

When the line energy (laser power divided by the welding speed) exceeded 6 J/mm, then instead of a single uniform weld, a weak interface was formed in the track (area illuminated by the laser beam) with strong fringes formed near the edge. All samples that were welded with a line energy of 6.25 J/mm or higher showed at least some failed weld interface. Samples with a line energy of 6 J/mm or less all failed only through the EPDM.

Reference: Xu XQ, Huang YP, Watt D, Baylis B: Diode laser welding of EPDM based elastomers. ANTEC 2003, Conference proceedings, Society of Plastics Engineers, Nashville, May 2003.

43.2 Fluoroelastomer

43.2.1 Adhesive Bonding

DuPont: Viton (note: compounded)

Viton can be adhered to a variety of metals, using special adhesive formulations also based on Viton. Assemblies do not fail at the bond. Bond strength exceeds the tear strength of cured Viton, both at 75°F (24°C) and at temperatures as high as 400°F (204°C). The adhesive bonds also endure 500°F (260°C) heat aging. Table 43.1 lists representative peel adhesion values between Viton and some common metals.

Reference: *The Engineering Properties of Viton Fluoroelastomer*, Supplier design guide (E-46315-1), DuPont Company, 1987.

Table 43.1. Adhesion of Viton to Metals Using Special Adhesive Formulations also Based on Viton*

Metal	Original Measured at 75°F (24°C)	Aged 64 hr at 500°F (260°C); Measured at 75°F (24°C)	Aged 64 hr at 500°F (260°C); Measured at 400°F (204°C)
Aluminum	160 (28.6)	20 (3.6)	6 (1.1)
Brass	160 (28.6)	20 (3.6)	6 (1.1)
Steel	160 (28.6)	20 (3.6)	6 (1.1)

*180° peel adhesion in lb/linear in. (kg/cm). All failures were by stock tearing.

43.3 Polyurethane

43.3.1 Ultrasonic Welding

Urethane (features: 5.8 mm (0.23 inches) thick)

Thermosetting urethanes will degrade when subjected to ultrasonic energy.

Reference: *Ultrasonic Sealing and Slitting of Synthetic Fabrics*, Supplier technical report, Sonic & Materials, Inc.

Table 43.2. Advanta Adhesive Recommendations Based on Data Provided by Lord Corporation

Formulations	Advanta 3320	Advanta 3650
Adhesive recommendations	Chemlok 607	Chemlok 610
	Chemlok 610	Chemlok 5150
	EP6964-07	Chemlok 5151
		EP6964-07

43.4 Rubber Alloy

43.4.1 Adhesive Bonding

Dupont Dow Elastomers: Advanta 3320 (features: peroxide curable); **Advanta 3650** (features: peroxide curable)

High quality bonded parts (metal and plastic substrates) may be readily produced with Advanta polyethylene copolymer/fluoroelastomer alloy using commercial primers and bonding agents routinely recommended for fluoroelastomers. Specific recommendations are in Table 43.2.

Reference: *Product Information—3320 and 3650*, Supplier technical report (H-59831-1), DuPont Dow Elastomers, 1994.

Glossary

ABS—See *acrylonitrile-butadiene-styrene polymer*.

ABS nylon alloy—Thermoplastic alloy of ABS and nylon suitable for injection molding. Has properties similar to ABS but considerably higher elongation at yield.

ABS polycarbonate alloy—Thermoplastic alloy of ABS and polycarbonate suitable for injection molding and extrusion. Has properties similar to ABS. Used in automotive applications.

ABS polyurethane alloy—Thermoplastic alloy of ABS and polyurethane.

absolute density—See *density*.

absolute gravity—See *density*.

accelerator—A chemical substance that accelerates a chemical, photochemical, biochemical, etc., reaction or process, such as crosslinking or degradation of polymers, that is triggered and/or sustained by another substance, such as a curing agent or catalyst, or environmental factors, such as heat, radiation, or a microorganism. Also called activator, cocatalyst, promoter.

acetal—See *acetal resin*.

acetal resin—Thermoplastics prepared either by homopolymerization of formaldehyde or its trimer, trioxane, or by copolymerization of trioxane with other monomers such as ethylene oxide. Acetals have high impact strength, stiffness, and yield stress; low friction coefficient and gas and vapor permeability; good dimensional stability and dielectric properties; high fatigue strength; and good retention of properties at elevated temperatures. The homopolymer has higher heat deflection temperature but lower continuous use temperature than copolymers. All acetals have poor resistance to acids and homopolymers also show poor resistance to alkalies. Acetals are subject to UV degradation, are flammable, and are difficult to bond. Processed by injection and blow molding and extrusion. Used in mechanical parts such as gears and bearings, automotive parts such as window cranks and trim fasteners; appliances; pump housings, shower heads, and other plumbing applications; and electronics such as connectors. Also called acetal, polyformaldehyde, polyoxymethylene, POM.

acetone—A volatile, colorless, highly flammable liquid with molecular formula CH_3COCH_3. Acetone has an autoignition temperature of 537°C (999°F), mixes readily with water and some other solvents and is moderately toxic. Acetone dissolves most thermoplastics and some thermosets. Used as an organic synthesis intermediate (e.g., in the manufacture of bisphenol A and antioxidants), as a solvent in paints and acetate fiber spinning and for cleaning of electronic parts. Also called dimethyl ketone.

acetylene dichloride—See *dichloroethylene 1,2*.

acrylate resin—See *acrylic resin*.

acrylate-styrene-acrylonitrile polymer—Acrylic rubber-modified thermoplastic having high outdoor weatherability (e.g., retention of color, gloss, and impact and tensile properties). The material offers high gloss, good heat and chemical resistance, great toughness and rigidity, and very good antistatic properties. It is compatible with other polymers such as PVC and polycarbonate and processable by (co)extrusion, thermoforming, injection molding, structural foam molding, and extrusion-blow molding. Drying is necessary because the material is mildly hygroscopic. Used in building and construction, leisure and recreation, and automotive applications when there is a demand for good weatherability (e.g., commercial siding, exterior auto trim, outdoor furniture). Also called acrylic-styrene-acrylonitrile polymer, acrylonitrile-styrene-acrylate polymer, ASA.

acrylate-styrene-acrylonitrile polymer polyvinyl chloride alloy—Thermoplastic alloy of an acrylate-styrene-acrylonitrile polymer with polyvinyl chloride.

Acrylic epoxy resin—See *vinyl ester resin*.

Acrylic ethylene rubber—See *ethylene acrylic rubber*.

acrylic resin—The class of thermoplastics comprised of homopolymers and copolymers of alkyl (meth)acrylates. The most common monomers used are methyl and ethyl (meth)acrylates; the comonomers include other unsaturated monomers. The acrylic resins offer excellent optical clarity, weatherability and resistance to sunlight, outstanding surface hardness, good chemical resistance, rigidity, good impact strength, excellent dimensional stability, and low mold shrinkage.

They have poor solvent resistance, are subject to stress cracking, are combustible, and have low flexibility and thermal stability. The acrylic resins can be cast in sheets, rods, or tubing; extruded into sheets or profiles; injection molded; thermoformed; and coated. Applications include transparent items such as lenses, automotive trim, household items, light fixtures, conformed coatings on printed circuit boards, and medical devices. Also called acrylate resin, polyacrylate.

acrylic resin polyvinyl chloride alloy—A thermoplastic alloy of an acrylic resin and polyvinyl chloride.

acrylic styrene acrylonitrile polymer—See *acrylate-styrene-acrylonitrile polymer.*

acrylonitrile butadiene rubber—See *nitrile rubber.*

acrylonitrile-butadiene-styrene polymer—Thermoplastic comprised of a mixture of styrene-acrylonitrile copolymer (SAN) and SAN-grafted butadiene rubber. They have high impact resistance, toughness, rigidity and processability, but low dielectric strength, continuous service temperature, and elongation. Outdoor use requires protective coatings in some cases. Plating grades provide excellent adhesion to metals. Processed by extrusion, blow molding, thermoforming, calendaring and injection molding. Used in household appliances, tools, nonfood packaging, business machinery, interior automotive parts, extruded sheet, pipe and pipe fittings. Also called ABS.

acrylonitrile copolymer—Thermoplastic prepared by copolymerization of acrylonitrile with minor amounts of other unsaturated monomers. The class of acrylonitrile copolymers include ASA, ABS, SAN, and nitrile resins. In a narrower sense the term acrylonitrile copolymers is often used to denote (high) nitrile (barrier) resins. These resins have good gas barrier properties, chemical resistance, and taste and odor retention properties. These resins have moderately high tensile properties and good impact properties when rubber modified or oriented. Processed by extrusion, injection molding, and thermoforming. Used mainly in food and nonfood packaging. FDA approved for direct contact with food with some limitations.

acrylonitrile-methyl-acrylate copolymer—A thermoplastic polymer of acrylonitrile-methyl-acrylate.

acrylonitrile rubber—See *nitrile rubber.*

acrylonitrile-styrene-acrylate polymer—See *acrylate-styrene-acrylonitrile polymer.*

activation energy—An excess energy that must be added to an atomic or molecular system to allow a process, such as diffusion or chemical reaction, to proceed.

activator—See *accelerator.*

adherend—A body held to another body, usually by an adhesive. A part or detail being prepared for bonding.

adhesion promoter—*See primer.*

adhesive—A material, usually polymeric, capable of forming permanent or temporary surface bonds with another material as is or after processing such as curing. Used for bonding and joining. Many classes of adhesives include hot-melt, pressure-sensitive, contact, UV-cured, emulsion, etc.

adhesive abrasion—In adhesive bonding, a surface preparation technique in which the part surface is mechanically abraded in the presence of liquid adhesive. Abraded, adhesive-coated adherends are then mated, and the adhesive is allowed to cure. It is speculated that abrasion in the presence of adhesive creates free radicals that react directly with the adhesive; when abrasion is performed in the absence of adhesive, the generated free radicals are scavenged by oxygen in air before the adhesive is applied. Adhesive abrasion is commonly used on fluorocarbons; bond strengths of Teflon (PTFE) were increased about 700% using this technique.

adhesive bonding—A method of joining two plastics or other materials in which an adhesive is applied to the part surfaces. Bonding occurs through mechanical or chemical interfacial forces between the adhesive and adherend and/or by molecular interlocking. Surface preparation of the adherends and curing of the adhesive may be required.

adhesive failure—Failure of an adhesive bond at the adhesive-adherend interface. An example is an adhesive failure that leaves adhesive all on one adherend, with none on the other adherend. Adhesive failure is less desirable than cohesive failure because it is indicative of a joint with lower adhesive strength. See also *cohesive failure.*

adiabatic—A process in which there is no gain or loss of heat from the system to the environment. For plastics, although not completely correct, it is used to describe a mode of extrusion in which no external heat is added to the extruder. Heat may be removed from the extruder by cooling in order to keep the output temperature of the melt passing through the extruder constant. Heat input in this process originates from the conversion of mechanical energy of the screw to thermal energy.

adipic acid hexanediamine polymer—See *nylon 66.*

adsorption—Retention of a substance molecule on the surface of a solid or liquid. Also called physical adsorption.

aesthetic—Concerned with appearance and visual qualities (of a weld).

alignment—Relative position of parts.

alpha cellulose—See *cellulose*.

amideimide resin—See *polyamide-imide*.

amorphous nylon—Transparent products that typically involve rings in copolymer chains. See also *nylon 6/3T.*

amplitude—The maximum displacement of a particle.

amplitude transformer—See *booster*.

annealing—A process in which a material, such as plastic, metal, or glass, is heated then cooled slowly. In plastics and metals, it is used to reduce stresses formed during fabrication. The plastic is heated to a temperature at which the molecules have enough mobility to allow them to reorient to a configuration with less residual stress. Semicrystalline polymers are heated to a temperature at which retarded crystallization or recrystallization can occur.

antimonic acid—See *antimony pentoxide*.

antimonic anhydride—See *antimony pentoxide*.

antimony oxide—See *antimony trioxide*.

antimony pentoxide—(SbO_5) A white or yellowish powder that melts at 450°C (842°F). Loses oxygen above 300°C (572°F). Soluble in strong bases, forming antimonates; slightly soluble in water; insoluble in acids except for concentrated hydrochloric acid. Derived by reaction of concentrated nitric acid with the metal or trioxide. Used as a flame retardant for textiles and in the preparation of antimonates and other antimony compounds. Also called antimonic acid, antimonic anhydride, stibic anhydride.

antimony trioxide—(Sb_2O_3) A white, odorless, crystalline powder that melts at 655°C (1211°F). Soluble in concentrated hydrochloric and sulfuric acids and strong bases; insoluble in water. Amphoteric, a suspected carcinogen. Derived by reaction of ammonium hydroxide with antimony chloride, combustion of antimony in air, or directly from low-grade ores. Used in flameproofing textiles, paper, and plastics, especially polyvinyl chloride; glass decolorizer; paint pigments; staining of copper and iron; opacifiying ceramics; and as a catalyst or intermediate in organic reactions. Also called antimony oxide, antimony white.

antimony white—See *antimony trioxide.*

aramid—See *aromatic polyamide*.

aromatic ester carbonate—See *aromatic polyester estercarbonate*.

aromatic polyamide—Fiber spun from 100% sulfuric acid solution. Usually yellow in color. High strength, good impact resistance, abrasion resistance and chemical resistance. Applications include bullet-proof vests, sails, aircraft body parts, and sporting goods. Also called aramid.

aromatic polyester—Thermoplastic prepared by polycondensation of aromatic polyol with aromatic dicarboxylic acid or anhydride or by polycondensation of aromatic hydroxycarboxylic acid. They are tough, durable, heat resistant, and offer good dimensional stability, dielectric properties, UV-stability, and flame retardance. Chemical resistance of aromatic polyesters is somewhat lower than other engineering plastics. Processing is achieved by injection and blow molding, extrusion, and thermoforming. Thorough drying is required. Uses include automotive housings and trim, electrical wire jacketing, printed circuit boards, appliance enclosures. Also called ARP, polyarylate.

aromatic polyestercarbonate—See *aromatic polyester estercarbonate*.

aromatic polyester estercarbonate—A thermoplastic comprising block copolymer of an aromatic polyester with polycarbonate. It has increased heat distortion temperature, compared to general-purpose polycarbonate. Also called aromatic ester carbonate, aromatic polyestercarbonate, polyestercarbonate.

ARP—See *aromatic polyester*.

ASA—See *acrylate-styrene-acrylonitrile polymer*.

ASA PVC alloy—Alloy of acrylate-styrene-acrylonitrile and polyvinyl chloride.

aseptic—In food processing, a process or condition that renders a processed food product essentially free of microorganisms capable of growing in the food in unrefrigerated distribution and storage conditions. In aseptic food packaging, presterilized containers are filled with aseptic foods, then hermetically sealed in a commercially sterile atmosphere.

ASTM D1002—An American Society for Testing of Materials (ASTM) standard practice for testing the shear strength of rigid sheet material by tensile loading. Two sections of a rigid sheet material, usually 4 in. in length × 1 in. in width × 0.064 in. in thickness (102 × 25 × 1.62 mm) and having suitably treated surfaces, are overlapped 0.5 in. (12.7 mm) and adhesively bonded together in a 0.5 square inch contact area (323 mm^2). Both ends are then clamped firmly into the jaws of a tensile testing machine, and the the jaws are moved apart at a speed of 0.05 in./min. (1.3 mm/min.) until joint failure occurs. The failing load (in psi (MPa)) and mode of failure (adhesive, cohesive, or mixed) are reported. This is the most commonly used shear test for metal-to-metal structural adhesives. Although it is useful for quality control and comparing different adhesives, failure strength values are not useful for engineering design due to the complex stress distribution pattern in the adhesive with this joint configuration. Also called lap shear test.

ASTM D1761—An American Society for Testing of Materials (ASTM) standard practice for testing the strength and performance of mechanical fasteners in wood. Withdrawal resistance of wood to nails, staples, and screws is measured by recording the maximum load of fasteners withdrawn at a uniform rate of speed by a testing machine. Resistance of nails, staples, and screws to lateral movement is tested by tensile loading. Strength and rigidity of timber joints fastened with bolts or other metal connectors is tested by measuring the deformation of the joint at various intervals of loading. Vertical load capacity and torsional moment capacity of joist hangers is tested by measuring the amount of slip under load.

ASTM D4501—An American Society for Testing of Materials (ASTM) standard practice for determining the shear strengths of adhesives used to bond rigid materials by the block shear method. Adhesively bonded blocks, plates, or disks, with flash and fillets removed on the loaded side, are mounted into the shear fixture of a testing machine (capacity not less than 44 kN (10,000 lbf)). Test specimens can be any size within the limits of the shearing fixture capacity. The shear fixture is mounted into the testing machine in such a way that one adherend is engaged by the holding block and the other by the shearing tool. A crosshead speed of 0.05 inches/min (1.27 mm/min) is used for testing. The maximum force sustained by the specimen is recorded. This test is particularly applicable for testing bonds between ceramic, glass, magnet moldings, and plastic parts with one flat face in which machining is difficult or impractical.

average molecular weight—See *molecular weight*.

B

bar—A metric unit of measurement of pressure equal to 1.0E+06 dynes/cm^2 or 1.0E+05 pascals. It has a dimension of unit of force per unit of area. Used to denote the pressure of gases, vapors and liquids.

barrier material—Materials such as plastic films, sheeting, wood laminates, particle board, paper, fabrics, etc. with low permeability to gases and vapors. Used in construction as water vapor insulation, food packaging, protective clothing, etc.

base plate—Metal plate used to hold the component tooling in the welding machine.

base resin melt index—See *melt index*.

BCF welding—See *bead and crevice free welding*.

bead and crevice free welding—A flash free welding technique for thermoplastic pipes, especially PVDF, which uses a heated metal collar on the outside of the pipe and an inflated bladder on the inside to constrain the melt during welding. Used in the semiconductor, pharmaceutical and food processing industries. Also called BCF welding. See also *flash free welding*.

beading—In joining plastics, bending an edge of a flat thermoplastic sheet, using roll(s) with or without heating, or flanging an end of a thermoplastic pipe, using a mandrel with or without heating, to form a profile suitable for subsequent joining or assembly. In coating, heavy accumulation of a coating which occurs at the lower edge of a panel or other vertical surface as the result of excessive flowing.

bending strength—See *flexural strength*.

benzene—An aromatic hydrocarbon with six-atom carbon ring, C_6H_6. Highly toxic and flammable (autoignition point 562°C (1044°F)). A colorless or yellowish liquid under normal conditions (b.p. 80.1°C (176.2°F)), soluble in many organic solvents such as ethanol, acetone, tetrachlorocarbon, etc. Used for synthesis of organic compounds.

bisphenol A epoxy resin—See *epoxy resin*.

bisphenol A fumarate polyester—See *bisphenol A polyester*.

bisphenol A polyester—A thermoset unsaturated polyester based on bisphenol A and fumaric acid. Also called bisphenol A fumarate polyester.

black lead—See *graphite filler*.

blooming—A phenomenon associated with cyanoacrylate adhesives seen as a white powdery residue on substrate material.

blush—The formation of condensate in a solvent bond resulting from the cooling of the surface due to the rapid evaporation of a low boiling point solvent.

booster—In ultrasonic welding, a mechanical transformer used to increase or decrease the amplitude of the horn. Also called amplitude transformer, booster horn, impedance transformer.

booster horn—See *booster.*

boss—A hollow or solid projection used for attachment and support of related components. Properly designed bosses and ribs can provide dimensional stability to the part, while reducing material usage and molding cycle time. In mechanical fastening, the hollow projection into which an insert or screw is driven. Solid bosses are also called studs.

breaking elongation—See *elongation*.

bursting strength—Minimum force per unit area or pressure required to produce rupture in, for example, a plastic film. The pressure is applied with a ram or a diaphragm at a controlled rate to a specified area of the material held rigidly and initially flat but free to bulge under the increasing pressure.

butadiene-styrene block copolymer—See *styrene-butadiene block copolymer*.

butadiene-styrene-methyl methacrylate polymer—-See *methyl methacrylate-butadiene-styrene terpolymer*.

butanone—($CH_3COCH_2CH_3$) A colorless liquid with an acetone-like odor. Soluble in benzene, alcohol, ether; partially soluble in water; miscible with oils. Its TLV is 200 ppm in air; it is toxic by inhalation and a dangerous fire risk. Explosive limit in air is 2–10%. Derived from sulfuric acid hydrolysis of mixed n-butylenes followed by distillation, by controlled oxidation of butane, or by fermentation. Used as a solvent in nitrocellulose coatings and vinyl films and in paint removers, cements and adhesives, manufacture of smokeless powder, cleaning fluids, and acrylic coatings. Used in printing, and as a reagent for organic synthesis. Also called ethyl methyl ketone, MEK, methyl ethyl ketone.

butt fusion welding—See *heated tool welding.*

butt joint—A type of edge joint in which the edge faces of the two parts are at right angles to the other faces of the part.

butt joint weld—A weld in which the parts are joined using a butt joint.

C

CA—See *cellulose acetate*.

CAB—See *cellulose acetate butyrate*.

capillary method—A method of solvent welding where a low viscosity solvent is applied to the joint using a hypodermic needle and flows through the joint area by capillary action.

caprolactam pyrrolidone polymer—See *nylon 46*.

carbon black—Black colloidal carbon filler made by the partial combustion and/or thermal cracking of natural gas, oil, or another hydrocarbon. Depending upon the starting material and the method of manufacture, carbon black can be called acethylene black, channel black, furnace black, etc. For example, channel black is made by impinging gas flames against steel plates or channel irons, from which the deposit is scraped at intervals. The properties and the uses of each carbon black type can also vary. Thus, furnace black comes in high abrasion, fast extrusion, high modulus, general purpose, and semi-reinforcing grades among others. Carbon black is widely used as a filler and pigment in PVC, phenolic resins, and polyolefins. It increases the resistance to UV light and electrical conductivity and sometimes acts as a cross-linking agent. Also called colloidal carbon.

carbon fiber—High-performance reinforcement consisting essentially of carbon. They are made by a variety of methods including pyrolysis of cellulosic (e.g., rayon) and acrylic fibers, burning-off binder from a pitch precursor, and growing single crystals (whiskers) via thermal cracking of hydrocarbon gas. The properties of carbon fibers depend on the morphology of carbon in them and are the highest for crystalline carbon (graphite). These properties include high modulus and tensile strength, high thermal stability, electrical conductivity, chemical resistance, wear resistance, and relatively low weight. Used as continuous or short fibers and in mats in autoclave and die molding, filament winding, injection molding, and pultrusion. Carbon fibers are used at a loading levels of 20–60 vol% or more in both thermosets and thermoplastics such as epoxy resins and ABS. Carbon fibers are often used in combination with other fibers such as glass fibers to make hybrid composites. The end products containing carbon fibers include wheelchairs, tennis racquets, auto parts, machine tools, and support structures in electronic equipment. Also called graphite fiber.

carbon filler—A family of fillers based on carbon in various forms, such as carbon black and graphite. Used as a black pigment, to improve lubricity, and to increase electrical conductivity of plastics. Also called carbon powder, powdered carbon.

carbon graphite—See *graphite filler*.

carbon powder—See *carbon filler*.

carbon tetrachloride—(CCl_4) A colorless liquid with a sweet odor. Miscible with alcohol, ether, chloroform, benzene, solvent naphtha, and most fixed and volatile oils; insoluble in water. Noncombustible. Boils at 76.7°C (170.1°F); freezes at –23°C (–9.4°F); vapor is 5.3 times heavier than air. Its TLV is 5 ppm in air; it is toxic by ingestion, inhalation, and skin absorption. Decomposes to phosgene at high temperatures. Derived by reaction of carbon disulfide and chlorine in the presence of iron or by chlorination of methane or higher hydrocarbons at 250–400°C (482–752°F). Purified by removal of sulfur chloride using caustic alkali, followed by rectification. Used in metal degreasing, chlorination of organic compounds, the production of semiconductors and solvents (fats, oils, rubber); as a refrigerant and agricultural fumigant. Also called perchloromethane, tetrachloromethane.

cast film—Film produced by pouring or spreading resin solution or melt over a suitable temporary substrate, followed by curing via solvent evaporation or melt cooling and removing the cured film from the substrate.

CE—See *cellulosic plastic*.

cellulose—Natural carbohydrate polymer of high molecular weight comprised of long chains of D-glucose units joined together by β-1,4-glucasidic bonds. It is derived from plants such as cotton and trees. It is used to produce cellulose esters and ethers (i.e., cellulosic plastics), but the largest use is in paper manufacture. Cellulose fillers in a narrow sense are usually made from wood pulp. In a broader sense they may include cotton lint, wood flour, lignin, wood chips, and various cellulosic waste such as cotton fiber rejects. Treating wood pulp with alkali results in a colorless filler used in thermosetting resins such as phenolic. Also called alpha cellulose, cellulose pulp, pulp.

cellulose acetate—Thermoplastic ester of cellulose and acetic acid which is characterized by toughness, gloss, clarity, good processability, stiffness, hardness, good “feel”, and dielectric properties. The disadvantages of this ester include poor resistance to solvents, alkaline materials, and fungi, high moisture pickup and permeability, rather low compressive strength, and flammability. It is processed by injection and blow molding and extrusion. Applications include telephone and appliance cases, automotive steering wheels, pens and pencils, tool handles, tubular containers, eyeglass frames, brushes, tapes, sheeting, and signs. Also called CA.

cellulose acetate butyrate—Thermoplastic mixed ester of cellulose and acetic and butyric acids. Characterized by toughness, gloss, clarity, good processability, low temperature impact strength, dimensional stability, weatherability, good “feel”, and dielectric properties. The disadvantages of this ester include poor resistance to solvents, alkaline materials, and fungi, high moisture pickup and permeability, rather low compressive strength, and flammability. It is processed by injection and blow molding and extrusion. The applications include telephone and appliance cases, automotive steering wheels, pens and pencils, tool handles, tubular containers, eyeglass frames, brushes, tapes, sheeting, and signs. Also called CAB, cellulose butyrate.

cellulose butyrate—See *cellulose acetate butyrate*.

cellulose propionate—Thermoplastic ester of cellulose and propionic acid which is characterized by toughness, gloss, clarity, good processability, low temperature impact strength, dimensional stability, weatherability, good “feel”, and dielectric properties. The disadvantages of this ester include poor resistance to solvents, alkaline materials, and fungi, high moisture pickup and permeability, rather low compressive strength, and flammability. It is processed by injection and blow molding and extrusion. The applications include telephone and appliance cases, automotive steering wheels, pens and pencils, tool handles, tubular containers, eyeglass frames, brushes, tapes, sheeting, and signs. Also called CP.

cellulose pulp—See *cellulose*.

cellulosic—See *cellulosic plastic*.

cellulosic plastic—A class of thermoplastics consisting of cellulose esters and ethers. The most important esters are acetates, including mixed esters, and nitrates. The most important ethers are ethyl and carboxymethyl. The cellulosic plastics are characterized by toughness, gloss, clarity, and good processability. In addition, the acetates exhibit good stiffness and hardness, the butyrates and propionates show increased weatherability, low temperature impact strength, and dimensional stability, and all esters have good “feel” and dielectric properties. The disadvantages of the esters include poor resistance to solvents, alkaline materials, and fungi, high moisture pickup and permeability, rather low compressive strength, and flammability. They are processed by injection and blow molding and extrusion. The applications include telephone and appliance cases, automotive steering wheels, pens and pencils, tool handles, tubular containers, eyeglass frames, brushes, tapes, sheeting, and signs. Also called CE, cellulosic.

chain scission—Breaking of the chainlike molecule of a polymer as a result of chemical, photochemical, etc. reaction such as thermal degradation or photolysis.

chamfer—A beveled edge or corner; to bevel a sharp edge.

chemical saturation—Absence of double or triple bonds in a chain organic molecule such as that of most polymers, usually between carbon atoms. Saturation makes the molecule less reactive and polymers less susceptible to degradation and crosslinking.

chemical unsaturation—Presence of double or triple bonds in a chain organic molecule such as that of some polymers, usually between carbon atoms. Unsaturation makes the molecule more reactive, especially in free-radical addition reactions such as addition polymerization, and polymers more susceptible to degradation, crosslinking and chemical modification.

chlorendic polyester—A thermoset unsaturated polyester based on chlorendic anhydride.

chlorinated polyvinyl chloride—Thermoplastics produced by post-chlorination of PVC to increase glass temperature and heat deflection under load. Have high chemical resistance, rigidity, flame retardance, tensile strength, and weatherability. Processed by extrusion, injection molding, casting, and calendering. Used in hot and cold water piping and fittings, chemical liquid piping, automotive parts, waste disposal devices, outdoor applications, and glazing beads. Also called chlorinated PVC, CPVC, PVC-C.

chlorinated PVC— See *chlorinated polyvinyl chloride*.

chloroprene rubber—See *neoprene rubber*.

chlorosulfonated PE rubber—See *chlorosulfonated polyethylene rubber*.

chlorosulfonated polyethylene rubber—Thermosetting elastomers that contain between 20 and 40% chlorine and approximately 1–2% sulfur. They provide resistance to ozone and oxygen attack under sunlight and UV radiation conditions. They are also resistant to deterioration due to heat, chemicals, and solvents. The most common applications for these elastomers are hose, tubing, and sheet goods, soles and heels, life boats and jackets, and windbreakers. Also called chlorosulfonated PE rubber, CSM, CSPE rubber.

chopped glass fiber—Glass fibers that have lengths from 1/8 to ½ inch (3.2–12.7 mm), made by chopping glass strands. The individual fibers are bonded together within strands so that they can remain in bundles after chopping. Used widely in bulk molding compounds; and compression, transfer, and injection molding. Also called chopped strand, medium glass fiber, short glass fiber.

chopped strand—See *chopped glass fiber*.

chromic acid etching—In adhesive bonding, a surface preparation technique in which chromic acid is used to introduce oxygenated reactive molecular groups, such as hydroxl, carbonyl, carboxylic, and hydrogen sulfite, to the part surface and to form root-like cavities as sites for mechanical interlocking. Commonly used for polyolefins, ABS, polystyrene, polyphenylene oxide, and acetals.

CO_2 laser—These lasers are generated by an air cooled gas discharge, which produces a beam of light with principal bands around 9.4 and 10.6 nm. They are typically used for cutting and welding metals.

cobalt naphthenate—A brown, amorphous powder or bluish-red solid of indefinite composition. Soluble in alcohol, ether, and oils; insoluble in water. Combustible. Derived from reaction of cobaltous hydroxide or cobaltous acetate with naphthenic acids. Used as a catalyst in bonding rubber to steel and other metals and as a paint and varnish drier.

cobalt-60—One of the unstable isotopes of cobalt used widely as a source of gamma radiation.

COC—See *cyclic olefin copolymer*.

cocatalyst—See *accelerator*.

coefficient of expansion—A factor for the length or volume a material expands as the temperature is increased.

coextruded film—A film made by coextrusion of two or more different or similar plastics through a single die with two or more orifices arranged so that the extrudates merge and weld together into a laminar film before cooling. Each ply of coextruded film imparts a desired property, such as impermeability or resistance to some environment and heat sealability, usually unattainable with a single material.

cohesion—The force within a body holding it together.

cohesive failure—Failure of an adhesive bond that occurs within the adhesive, leaving adhesive present on both adherends. Optimum failure is 100% cohesive failure, when both shear areas are completely covered. See also *adhesive failure*.

colloidal carbon—See *carbon black*.

conditioning—Process of bringing the material or apparatus to a certain condition (e.g., moisture content or temperature) prior to further processing, treatment, etc. Also called conditioning cycle.

conditioning cycle—See *conditioning*.

conduction—In heat transfer, migration of energy due to a temperature gradient. Heat energy is transferred by the movement of molecules at hotter or colder temperatures, with different degrees of thermal motion, into colder or hotter regions, respectively. See also *convection, radiation*.

contact adhesive—An adhesive that will adhere to itself on contact. When applied to both adherends, it forms a bond after drying, without sustained pressure on the adherends. Composed of neoprene or, less commonly, nitrile elastomers. See also *pressure sensitive adhesive*.

continuous glass fiber—Strands of filaments (roving) made by melt drawing from various grades of glass. Can be twisted. Used in sheet molding compounds, sprayup lamination, pultrusion, and filament winding. Continuous glass fibers provide fast wetout, even tension, and abrasion resistance during processing. Also called continuous glass roving, continuous roving, continuous strand roving, long glass fiber.

continuous glass roving—See *continuous glass fiber*.

continuous roving—See *continuous glass fiber*.

continuous strand roving—See *continuous glass fiber*.

convection—The mass movement of particles arising from the movement of a streaming fluid due to a difference in a physical property such as density, temperature, etc. Mass movement due to a temperature difference results in heat transfer, as in the upward movement of a warm air current. See also *conduction, radiation*.

converter—See *transducer*.

copolyester—See *polyester*.

copolyester thermoplastic rubber—See *polyester thermoplastic elastomer*.

copolyester TPE—See *polyester thermoplastic elastomer*.

copy milling—Action of machining used to accurately reproduce a component.

corona discharge treatment—In adhesive bonding, a surface preparation technique in which a high electric potential is discharged by ionizing the surrounding gas, usually air. The gas reacts with the plastic, roughening the surface to provide sites for mechanical interlocking and introducing reactive sites on the surface. Functional groups such as carbonyls, hydroxyls, hydroperoxides, aldehydes, ethers, esters, carboxylic acids, and unsaturated bonds have been proposed as reactive sites. Commonly used for polyolefins, corona discharge increases wettability and surface reactivity. In processing plastics, treating the surface of an inert plastic such as polyolefin with corona discharge to increase its affinity to inks, adhesives or coatings. Plastic films are passed over a grounded metal cylinder with a pointed high-voltage electrode above it to produce the discharge. The discharge oxidizes the surface, making it more receptive to finishing. Also called corona treatment. See also *plasma arc treatment*.

corona treatment—See *corona discharge treatment*.

Coulombic friction—The opposing force that occurs when two dry surfaces are rubbed together, as in vibration and spin welding. Also called external friction. See also *internal friction*.

coupler—In ultrasonic welding, a booster that does not affect the amplitude of the horn. Its gain ratio is 1:1.

CP—See *cellulose propionate*.

CPVC—See *chlorinated polyvinyl chloride*.

cracking—Appearance of external and/or internal cracks in the material as a result of stress that exceeds the strength of the material. The stress can be external and/or internal and can be caused by a variety of adverse conditions: structural defects, impact, aging, corrosion, etc. or a combination thereof. Also called grazing. See also *crazing*.

crazing—Appearance of thin cracks on the surface or minute frost-like internal cracks in materials such as plastics as a result of residual stress, impact, temperature changes, degradation, etc. See also *cracking*.

creep—Time-dependent increase in strain in material, occuring under stress.

cross-linked PE—See *cross-linked polyethylene*.

cross-linked polyethylene—Polyethylene thermoplastic partially cross-linked by irradiation or by the use of chemical additives such as peroxides to improve tensile strength, dielectric properties and impact strength over a wider range of temperatures. Also called crosslinked PE, PEX.

cross-linking—Reaction or formation of covalent bonds between chain-like polymer molecules or between polymer molecules and low-molecular compounds such as carbon black fillers. As a result of cross-linking, polymers such as thermosetting resins, may become hard and infusible. Cross-linking is induced by heat, UV or electron-beam radiation, oxidation, etc. Cross-linking can be achieved either between polymer molecules alone as in unsaturated polyesters or with the help of multifunctional cross-linking agents such as diamines that react with functional side groups of the polymers. Cross-linking can be catalyzed by the presence of transition metal complexes, thiols and other compounds.

crystal polystyrene—See *general purpose polystyrene*.

crystal PS—See *general purpose polystyrene*.

crystalline melting point—The temperature of melting of the crystalline phase of a crystalline polymer. It is higher than the glass transition temperature of the surrounding amorphous phase.

CSM—See *chlorosulfonated polyethylene rubber*.

CSPE rubber—See *chlorosulfonated polyethylene rubber*.

CTFE—See *polychlorotrifluoroethylene*.

curing—A process of hardening or solidification involving crosslinking, oxidizing, and / or polymerization (addition or condensation).

cyanoacrylate—In adhesive bonding, a highly reactive class of adhesives that cures rapidly at room temperature with trace amounts of moisture as catalysts to form high strength bonds with plastics and metals.

cyanoguanidine—See *dicyandiamide*.

cyclic olefin copolymer—Amorphous polyolefin. It is transparent and has a high moisture barrier. It is primarily used for camera lenses, projectors, monitors and medical devices. Also called COC.

cyclohexane—(C_6H_{12}) A colorless liquid with a pungent odor. Molecular structure is an alicyclic hydrocarbon that can exist in two conformations, the "boat" and "chair," depending on bond angles between carbon atoms. Soluble in alcohol, acetone, benzene; insoluble in water. Boils at 80.7°C (177°F); freezes at 6.3°C (43°F). Its autoignition temperature is 260°F (500°F). It is a dangerous fire risk; flammable limit in air is 1.3–8.4%. Its TLV is 300 ppm in air; it is moderately toxic by inhalation and skin contact. Derived from crude petroleum or by catalytic hydrogenation of benzene. Used in the production of nylon, in the extraction of essential oils; as a solvent for cellulose ethers, fats, oils, crude rubber, bitumens, resins, waxes; in organic synthesis; as a paint and varnish remover and in glass substitutes. Also called hexalhydrobenzene, hexamethylene, hexanaphthene.

cyclohexanone—($C_6H_{10}O$) Oily, water-white to pale yellow liquid with a slight odor of peppermint and acetone. Soluble in organic solvents such as alcohols and ethers, slightly soluble in water. It has an autoignition temperature of 420°C (788°F). Its TLV is 25 ppm in air; it is toxic by inhalation and skin contact. Derived by passing cyclohexanol over copper with air at 138°C (280°F) or by oxidation of cyclohexanol with chromic acid or oxide. Used in the preparation of adipic acid, caprolactam, polyvinyl chloride and its copolymers, and methacrylate ester polymers, and for metal degreasing. Used in wood stains, paint and varnish removers, spot removers, polishes, natural and synthetic resins, lube oil, and other products. Also called ketohexamethylene, pimelic ketone.

D

DAIP—See *diallyl phthalate*.

damping—In part assembly, to mechanically limit the amplitude of vibration in the parts being assembled.

DAP—See *diallyl phthalate*.

dart impact energy—See *falling weight impact energy*.

dart impact strength—See *falling weight impact energy*.

DCM—See *dichloromethane*.

deflection temperature under load—See *heat deflection temperature*.

degradation—Loss or undesirable change in properties as a result of aging, chemical reactions, wear, use, exposure, etc. The properties include color, size, strength, etc.

density—The mass of any substance (gas, liquid or solid) per unit volume at specified temperature and pressure. The density is called absolute when measured under standard conditions (e.g., 760 mmHg pressure and 0°C (32°F) temperature). Note: for plastics, the weight in air per volume of impermeable portion of the material measured at 23°C (73.4°F) according to ASTM D792. Also called absolute density, absolute gravity, mass density.

diallyl isophthalate—See *diallyl phthalate*.

diallyl isophthalate resin—See *diallyl phthalate*.

diallyl phthalate—Thermoset resins comprised of diallyl (iso)phthalate prepolymer. Sometimessupplied as a monomer. These resins show excellent moisture resistance, high service temperatures, good retention of electrical properties under high temperature and humidity, dimensional stability, chemical resistance (except for phenols and oxidizing acids), and good mechanical strength. The disadvantages include high cost and shrinkage during curing. Cured by peroxide catalysts. Processed by injection, compression, and transfer molding. Used in glass fiber-reinforced plastic articles such as tubing and in the manufacture of automotive distribution caps, electronic connectors, and transformer cases. Also called DAIP, DAP, diallyl isophthalate, diallyl isophthalate resin, diallyl phthalate resin, PDAP.

diallyl phthalate resin—See *diallyl phthalate*.

diaphragmming—Part flexing that can cause stress, fracturing, or undesirable melting of thin-sectioned, flat parts. Also called "oil-canning", which describes the way the plastic part bends up and down when subjected to ultrasonic energy.

dichloroethylene 1,2—(ClCH:CHCl) A colorless liquid with a pleasant odor. Exists as cis and trans stereoisomers. Soluble in most organic solvents; slightly soluble in water. Trans isomer boils at 47–49°C (116–120°F); cis isomer boils at 58–60°C (136–140°F) and freezes at –80°C (–112°F). Its TLV is 200 ppm in air; it is toxic by ingestion, inhalation, and skin contact and is an irritant and narcotic at high concentrations. Flammable; a dangerous fire hazard. Used as a solvent for organic compounds and in organic synthesis; in dye extraction, perfumes, lacquers, and thermoplastics. Also called acetylene dichloride, sym-dichloroethylene.

dichloromethane—(CH_2Cl_2) A colorless, volatile liquid with an odor of ether. Boils at 40.1°C (104.2°F); freezes at –97°C (–143°F). Soluble in alcohol, ether; slightly soluble in water. Nonflammable and nonexplosive in air. It is a carcinogen and narcotic; its TLV is 100 ppm in air. Derived from the chlorination of methyl chloride, followed by distillation. Used as a refrigerant; in nonflammable paint removers; in plastics processing and solvent extraction; as a blowing agent in foams and an aerosol propellant; in solvent degreasing; and as a solvent in organic synthesis. Also called DCM, methylene chloride, methylene dichloride.

dicyandiamide—($NH_2C(NH)(NHCN)$) White crystals that are stable when dry. Soluble in liquid ammonia; partly soluble in hot water. Melts at 207–209°C (405–408°F). Not flammable. Derived from polymerization of cyanamide in the presence of bases. Used as a catalyst for epoxy resins, a stabilizer in detergents, a modifier in starch products, a thinner in oil-well drilling muds; in organic reactions, fertilizers, pharmaceuticals, dyestuffs, case-hardening preparations, soldering compounds; and many other uses. Also called cyanoguanidine.

dielectric dissipation factor—The ratio of the power dissipated in a dielectric material to the product of the effective voltage and the current; or the cotangent of the dielectric phase angle; or the tangent of dielectric loss angle. Note: for plastics measured according to ASTM D150. Also called dielectric loss tangent, dissipation factor, permittivity loss factor, tan delta.

dielectric loss tangent—See *dielectric dissipation factor*.

dielectric welding—See *radio frequency welding*.

differential scanning calorimetry—Technique in which the energy absorbed or produced is measured by monitoring the difference in energy input into the substance and a reference material as a function of temperature. Absorption of energy produces an endotherm; production of energy results in an exotherm. May be applied to processes involving an energy change, such as melting, crystallization, resin curing, and loss of solvents, or to processes involving a change in heat capacity, such as the glass transition. Also called DSC.

dimethylene oxide—See *ethylene oxide*.

dimethyl ketone—See *acetone*.

diode laser—A laser where the active medium is a semiconductor similar to that found in a light-emitting diode. The most common and practical type of laser diode is formed from a p-n junction and powered by injected electrical current.

dip method—A method of solvent welding where the edges of the parts to be joined are dipped into a tray of solvent before being brought together to fuse. Also called soak method.

direct contact heated tool welding—See *heated tool welding*.

direct drive welding—Method of spin welding using continuously driven rotating machinery.

displacement—The reduction in component size perpendicular to the joint face caused by welding.

displacement transducer—Device used to measure magnitude of movement; used in displacement-controlled welding operations.

dissipation factor—See *dielectric dissipation factor*.

dissolving capacity—See *solubility*.

DMF—See *N,N-dimethylformamide*.

dodecanedioic acid hexamethylenediamine polymer—See *nylon 612*.

drive pin—See *locating pin*.

driving torque—In mechanical fastening, the force necessary to drive a self-tapping screw into a pilot hole. Lower values are optimal.

drop dart impact strength—See *falling weight impact energy*.

drop weight impact strength—See *falling weight impact energy*.

DSC—See *differential scanning calorimetry*.

durability—See *stability*.

durometer hardness—Indentation hardness of a material as determined by either the depth of an indentation made with an indentor under specified load or the indentor load required to produce a specified indentation depth. The tool used to measure indentation hardness of polymeric materials is called a durometer (e.g., Shore-type durometer).

E

EAA—See *polyethylene-acrylic acid copolymer*.

EA rubber—See *ethylene acrylic rubber*.

EAR—See *ethylene acrylic rubber*.

ECTFE—See *ethylene chlorotrifluoroethylene copolymer*.

EF welding—See *electrofusion welding*.

elasticity constant—See *modulus of elasticity*.

electrofusion welding—A resistive implant welding technique used for joining thermoplastic pipes or liners, in which electricity is applied to a heating element surrounded by a thermoplastic material. The heat produced causes the thermoplastic material and the thermoplastic on the surface of the pipes to melt and flow together, forming a weld. Commonly used for joining polyethylene pipes. Also called EF welding.

electromagnetic radiation—Waves of electric charges propagated through space by oscillating electromagnetic fields and associated energy.

electromagnetic welding—See *induction welding*.

electron beam—See *electron beam radiation*.

electron beam radiation—Ionizing radiation propagated by electrons that move forward in a narrow stream with approximately equal velocity. Also called electron beam.

Elmendorf tear strength—The resistance of flexible plastic film or sheeting to tear propagation. It is measured, according to ASTM D1922, as the average force, in grams, required to propagate tearing from a precut slit through a specified length, using an Elmendorf-type pendulum tester and two specimens, a rectangular type and one with a constant radius testing length.

elongation—The increase in gauge length of a specimen in tension, measured at or after the fracture, depending on the viscoelastic properties of the material. Note: elongation is usually expressed as a percentage of the original gage length. Also called breaking elongation, elongation at break, tensile elongation, ultimate elongation.

elongation at break—See *elongation*.

EMAC—See *ethylene methyl acrylate copolymer*.

EMA welding—See *induction welding*.

embrittlement—A condition of low ductility in metals resulting from chemical or physical damage.

energy director—A triangular shaped bead of plastic that is molded into one of the parts to be joined. Used in ultrasonic welding, it concentrates ultrasonic energy at the point, resulting in rapid heat buildup and melting.

environmental stress cracking—Cracking or crazing that occurs in a thermoplastic material subjected to stress or strain in the presence of particular chemicals or weather conditions or as a result of aging. Also called ESC.

EP—See *epoxy resin*.

EPDM—See *EPDM rubber*.

EPDM rubber—Rubber produced from ethylene, propylene, and smaller amounts of a nonconjugated diene such as hexadiene. They are vulcanized using sulfur. Typical properties include excellent resistance to oxygen, ozone, light, high and low temperatures, acids, alkalies, and oils. They may be used in other elastomers as impact modifiers and also to improve heat and ozone resistance. Typical uses include weather stripping, auto parts, cable insulation, conveyor belts, garden and industrial hoses, and appliance tubing. EPDM rubbers have been proposed as potential substitutes for natural rubber in tires. Also called EPDM, ethylene propylene diene monomer rubber.

epoxides—Organic compounds containing three-membered cyclic group(s) in which two carbon atoms are linked with an oxygen atom as in an ether. This group is called an epoxy group and is quite reactive, allowing the use of epoxides as intermediates in preparation of certain fluorocarbons and cellulose derivatives and as monomers in preparation of epoxy resins.

epoxy—See *epoxy resin*.

epoxy resin—Family of thermoset polyethers containing crosslinkable glycidyl groups. The largest group of epoxy resins is prepared by polymerization of bisphenol A and epichlorohydrin. These resins have a wide viscosity range, depending on their molecular weight, and are cured at room or elevated temperatures with catalized polyamines and/or anhydrides. Aliphatic and cycloaliphatic epoxy resins are produced by peroxidation of olefins with peracetic acid or epoxidation of polyols with epichlorohydrin. Novolak epoxy resins are prepared by reacting novolak phenolic resins with epichlorohydrin. Vinyl ester or acrylic epoxy resins are prepared by treating epoxy resins with unsaturated carboxylic acids such as acrylic acid. There are other specialty type epoxy resins such as halogenated epoxy and phenoxy resins. Bisphenol A epoxy resins exhibit excellent adhesion and very low shrinkage during curing. Additionally, cured novolak and cycloaliphatic resins have good UV stability and dielectric properties, while cured vinyl ester resins show high strength and chemical resistance and brominated epoxy resins show fire retardant properties. Some epoxy resins have poor oxidative stability. Processed by injection, compression, transfer, and structural foam molding, casting, coating, and lamination. Widely used as protective coatings, adhesives, potting compounds, and binders in laminates, flooring, civil engineering, electrical and electronic products. Also called bisphenol A epoxy resin, EP, epoxy.

epoxyethane—See *ethylene oxide*.

EPR—See *ethylene propylene rubber*.

EPS—See *expanded polystyrene*.

ESC—See *environmental stress cracking*.

etching—In adhesive and solvent bonding, a process used to prepare plastic surfaces for bonding. Exposure of the plastic parts to a reactive chemical, such as chromic acid, or to an electrical discharge results in oxidation of the surface and an increase in surface roughness by removal of surface material.

ETFE—See *ethylene tetrafluoroethylene copolymer*.

ethane—An alkane (saturated aliphatic hydrocarbon) with two carbon atoms, CH_3CH_3. A colorless, odorless, flammable gas. Relatively inactive chemically. Obtained from natural gas. Used in petrochemical synthesis and as fuel.

ethanol—See *ethyl alcohol*.

ethene—See *ethylene*.

ethyl acetate—An ethyl ester of acetic acid, CH_3CO_2-CH_2CH_3. A colorless, fragrant, flammable liquid. Autoignition temperature 426°C (799°F). Toxic by inhalation and skin absorption. Derived by catalytic esterification of acetic acid with ethanol. Used as a solvent in coatings and plastics, organic synthesis, artificial flavors, and pharmaceuticals.

ethyl alcohol—An aliphatic alcohol, CH_3CH_2OH. A colorless, volatile, flammable liquid. Autoignition point is 422°C (792°F). Toxic by ingestion. Derived by catalytic hydration of ethylene, fermentation of biomass such as grain, or enzymatic hydrolysis of cellulose. Used as automotive fuel additive, in alcoholic beverages, as solvent for resins and oils, in organic synthesis, cleaning compositions, cosmetics, antifreeze, and antiseptic. Also called ethanol.

ethylene—An alkene (unsaturated aliphatic hydrocarbon) with two carbon atoms, $CH_2{=}CH_2$. A colorless, highly flammable gas with sweet odor. Autoignition point 543°C (1009°F). Derived by thermal cracking of hydrocarbon gases or from gas synthesis. Used as a monomer in polymer synthesis, refrigerant, and anesthetic. Also called ethene.

ethylene-acrylic acid copolymer—See *polyethylene-acrylic acid copolymer*.

ethylene acrylic rubber—A thermosetting elastomer comprising a polymer of ethylene and acrylic ester. It is used in applications requiring a tough rubber with good low temperature properties and resistance to deterioration due to heat, oil, and water. Used for automotive, heavy equipment, and industrial parts. Also called acrylic ethylene rubber, EAR, EA rubber.

ethylene alcohol—See *ethylene glycol*.

ethylene chlorohydrin—(C_2H_5ClO) A colorless liquid easily soluble in most organic liquids and water. It has an autoignition temperature of 425°C (797°F) and is a moderate fire hazard. Derived by reaction of hydrochlorous acid with ethylene. It is a strong irritant, deadly via inhalation, skin absorption, etc. with a TLV of 1 ppm in air. Penetrates through rubber gloves. Used as a solvent for cellulose derivatives, intermediate in organic synthesis (e.g., for ethylene oxide) and sprouting activator. Note: hydrolysis of ethylene oxide during sterilization can result in the formation of ethylene chlorohydrin and its residual presence in sterilized goods. Also called glycol chlorohydrin.

ethylene chlorotrifluoroethylene copolymer—Thermoplastic alternating copolymer of ethylene and chlorotrifluoroethylene in a predominantly 1:1 ratio. Its strength, creep resistance, and wear resistance are significantly greater than those of other fluoropolymers. It has good dielectric properties and very high chemical resistance at room and elevated temperatures, and resists ignition and flame propagation. The service temperatures range from the cryogenic region to 166°C (330°F). The processing is carried out by molding, extrusion, rotomolding, and powder coating. Applications include wire and cable insulation, column packings, pump components, filter housings, tubing, linings, braided sleeving, and release films. Also called ECTFE.

ethylene glycol—($C_2H_6O_2$) A colorless heavy liquid soluble in polar organic solvents such as alcohols and water. It has an autoignition temperature of 413°C (775°F). Its TLV is 50 ppm and it is toxic by ingestion and inhalation. Derived by air oxidation of ethylene followed by hydration of resultant ethylene oxide, from gas synthesis, by oxirane process, etc. Used as a coolant and antifreeze, as a monomer for the production of polyesters, solvent additive, foam stabilizer, brake fluids and many other products. Note: Hydrolysis of ethylene oxide during sterilization can result in the formation of ethylene glycol and its residual presence in sterilized goods. Also called ethylene alcohol, glycol.

ethylene methyl acrylate copolymer—Thermoplastic resins prepared by high-pressure polymerization of ethylene and <40% methyl acrylate. The resins are characterized by good dielectric properties, toughness, thermal stability, and resistance to environmental stress cracking. They also have good processibility in LDPE equipment. They exhibit high compatibility with other polyolefins and permit high levels of filling. Optical properties deteriorate with increasing content of acrylate. Processed by blown film extrusion, extrusion, blow molding, and injection molding. Uses include coatings, heat-sealable film, disposable gloves, and anticeptic packaging. Meet FDA requirements for food packaging. Also called EMAC, methyl acrylate ethylene polymer.

ethylene oxide—(C_2H_4O) The simpliest, unsubstituted, saturated epoxide with molecular formula CH_2OCH_2. Ethylene oxide is a colorless gas at room temperature with autoignition temperature of 805°F (429°C). It is an eye and skin irritant and a suspected human carcinogen. Its TLV is 1ppm in air. It is a dangerous fire and explosion hazard. Ethylene oxide is derived by catalytic oxidation of ethylene or by alkaline hydrolysis of ethylene chlorohydrin. It is used in manufacture of ethylene glycol and other important chemicals such as polyethylene oxide surfactants, and as sterilant, fumigant and rocket propellant. Also called dimethylene oxide, epoxyethane, ETO, oxirane.

ethylene polymers—Polymers that include ethylene homopolymers and copolymers with other unsaturated monomers, most importantly olefins such as propylene and polar substances such as vinyl acetate. The properties and uses of ethylene polymers depend on the molecular structure and weight.

ethylene propylene diene monomer rubber—See *EPDM rubber*.

ethylene propylene rubber—Elastomers prepared by stereospecific polymerization of ethylene with propylene. The properties of EPR are similar to those of natural rubber. Used as impact modifiers for plastics and in tires. Also called EPR. See also *EPDM rubber*.

ethylene propylene terpolymer—A polymer consisting of ethylene, propylene and one component not identified.

ethylene tetrafluoroethylene copolymer—Thermoplastic comprised of an alternating copolymer of ethylene and tetrafluoroethylene. Has high impact resistance and good abrasion resistance, chemical resistance, weatherability, and electrical properties, approaching those of fully fluorinated polymers. Retains mechanical properties from cryogenic temperatures to 356°F (180°C). Can be molded, extruded, and powder coated. Used in tubing, cable and wire products, valves, pump parts, wraps, and tower packing in aerospace and chemical equipment applications. Also called ETFE.

ethylene-vinyl acetate—Encompasses a broad range of thermoplastics having vinyl acetate content between 5 and 50%. They have high toughness and flexibility, even at low temperatures, and good stress crack resistance. They are less crystalline than LDPE. EVAs can be injection and blow molded and extruded, and are used for packaging films, wire and cable insulation, adhesives and carpet backing. Also called EVA.

ethylene vinyl alcohol copolymer—Thermoplastics prepared by hydrolysis of ethylene-vinyl acetate copolymers. The resins have excellent gas and vapor barrier properties, high mechanical strength, gloss, elasticity, weatherability, and resistance to solvents and oils. The clarity, surface hardness, and abrasion resistance of EVOH resins are high. They absorb moisture which affects their performance as vapor barriers. The processibility of the resins improves and the absorption of moisture decreases with increasing content of ethylene. Processed by (co)extrusion, coating, blow molding, thermoforming, and film techniques. Used mainly as packaging films and container liners for food and nonfood items. Also called EVOH.

ethyl methyl ketone peroxide—See *methyl ethyl ketone peroxide*.

ETO—See *ethylene oxide*.

EVA—See *ethylene-vinyl acetate*.

EVOH—See *ethylene vinyl alcohol copolymer*.

expanded polystyrene—Produced from a mixture of around 90-95% polystyrene and 5-10% blowing agent, normally pentane or CO_2, which is expanded into foam through the use of heat, usually steam. Its density can vary from around 25 to 200 kg/m^3, depending on the amount of blowing agent used. Applications include packaging for foodstuffs and medical products, insulation panels for buildings, children's car seats and cycle helmets. Also called EPS.

extenders—Relatively inexpensive resin, plasticizer or filler such as carbonate used to reduce cost and/or to improve processing of plastics, rubbers or nonmetallic coatings.

external friction—See *Coulombic friction*.

extrusion welding—A joining process in which molten thermoplastic material is extruded into a groove in a preheated seam. The extruded thermoplastic material fills the groove and cools, welding the two parts together. Commonly used for joining membranes and pipes with thermoplastic liners.

F

falling dart impact strength—See *falling weight impact energy*.

falling weight impact energy—The mean energy of a free-falling dart or weight (tup) that will cause 50% failures after 50 tests to a directly or indirectly stricken specimen. The energy is calculated by multiplying dart mass, gravitational acceleration and drop height. Also called drop dart impact strength, drop weight impact strength, falling dart impact strength, falling weight impact strength.

falling weight impact strength—See *falling weight impact energy*.

far field—Refers to the distance that ultrasonic energy is transmitted from the horn to the joint interface in ultrasonic welding. Far field welding occurs when the joint is more than 0.25 in. (6.4 mm) from the point at which the horn contacts the part. See also *near field*.

FEP—See *fluorinated ethylene propylene copolymer*.

ferromagnetic material—Materials such as stainless steel and iron, in which the magnetic moments or dipoles of atoms exhibit a high degree of alignment parallel to each other in the presence of a magnetic field. This alignment is in opposition to the usual tendency of atoms to orient in random directions due to thermal motion. Used in induction welding.

fiber laser—A laser where the active gain medium is an optical fiber doped with rare-earth elements. Applications include materials processing, spectroscopy and medicine.

filler—Material, often particular, added to plastics to alter their properties or reduce cost.

fireproofing agent—See *flame retardant*.

fixture—A device used to align and support the parts during assembly. Used especially when the component has thin walls. Also called nest, tooling nest.

FKM—See *fluoroelastomer*.

flame retardant—A substance that reduces the flammability of materials such as plastics or textiles in which it is incorporated. There are inorganic flame retardants such as antimony trioxide (Sb_2O_3) and organic flame retardants such as brominated polyols. The mechanisms of flame retardation vary depending on the nature of the material and flame retardant. For example, some flame retardants yield a substantial volume of coke on burning, which prevents oxygen from reaching inside the material and blocks further combustion. Also called fireproofing agent.

flame treatment—In adhesive bonding, a surface preparation technique in which the plastic is briefly exposed to a flame. Flame treatment oxidizes the surface through a free radical mechanism, introducing hydroxyl, carbonyl, carboxyl, and amide functional groups to a depth of ~4–6 nm, and produces chain scissions and some cross-linking. Commonly used for polyolefins, polyacetals, and polyethylene terephthalate, flame treatment increases wettability and interfacial diffusivity.

flange—Strengthening material around a component perimeter.

flash—In welding thermoplastics, molten plastic that is forced out of the joint area during the welding process. In molding, surplus plastic attached to the molding along the parting line. Flash must usually be removed before parts are considered to be finished.

flash free welding—Welding techniques that do not generate any weld flash; the melt is fully constrained within the weld. See also *bead and crevice free welding*, *high performance fusion welding* and *flow fusion welding*.

flexural properties—Properties describing the reaction of physical systems to flexural stress and strain.

flexural strength—The maximum stress in the extreme fiber of a specimen loaded to failure in bending. Note: flexural strength is calculated as a function of load, support span and specimen geometry. Also called bending strength.

flexural stress—The maximum fiber stress in a specimen at a given strain in a bending test. The maximum fiber stress is a function of load, support span, and specimen width and depth. It depends on the method of load application relative to the supports and on the specimen geometry. Note: flexural stress is calculated as a function of load at a given strain or at failure, support span and specimen geometry.

flow fusion welding—A flash free welding technique for thermoplastic (especially fluoropolymer) sheets, where the melt is constrained during welding using heated metal bars above and below the joint. See also *flash free welding*.

fluorinated elastomer—See *fluoroelastomer*.

fluorinated ethylene propylene copolymer—Thermoplastic copolymer of tetrafluoroethylene and hexafluoropropylene. It has decreased tensile strength, wear resistance, and creep resistance compared to PTFE, but good weatherability, low dielectric constant, low flammability, low friction coefficient, and high chemical resistance. The material is useful up to 400°F (204°C); above this temperature FEP decomposes, releasing toxic products. The relatively low melt viscosity of FEP allows processing by conventional molding, extrusion, and powder coating. Uses include linings for chemical apparatus and pipes, containers, bearings, films, coatings, electric wires and cables. Also called FEP.

fluoro rubber—See *fluoroelastomer*.

fluorocarbon resin—See *fluoropolymer*.

fluoroelastomer—Class of synthetic elastomers designed for demanding service applications. They possess excellent resistance to corrosive fluids and other chemicals, as well as to high temperatures. Typical applications include automotive fuel line hoses, o-rings, shaft seals, engine oil and coolant seals, and carburetor fuel pumps. Fluoroelastomers may be used as additives for polyolefins to improve extrusion properties. Also called FKM, fluorinated elastomer, fluoro rubber.

fluorohydrocarbon resin—See *fluoropolymer*.

fluoroplastic—See *fluoropolymer*.

fluoropolymer—Thermoplastics comprised of mostly polyolefins that have all or some of the hydrogen atoms replaced by fluorine. Characterized by excellent chemical resistance, antifriction properties, thermal stability, antiadhesive properties, low flammability, and weatherability. The disadvantages include low creep resistance and strength and insufficient ease in processing. The properties of fluoropolymers depend on the content of fluorine. The processing is achieved by extrusion and molding. The uses are chemical apparatus, bearings, films, coatings, and containers. Also called fluorocarbon resin, fluorohydrocarbon resin, fluoroplastic, polyfluorocarbon, polyfluorohydrocarbon.

fluorosilicone—Synthetic polymers that are partly organic and partly inorganic. Their backbone is made up of alternating silicon and oxygen atoms with trifluoropropyl pendant groups. Most fluorosilicones are rubbers. Also called fluorosiloxane.

fluorosiloxane—See *fluorosilicone*.

flywheel—Rotating wheel used to store kinetic energy.

formula weight—See *molecular weight*.

Fourier transform infrared spectroscopy—Spectroscopic technique in which a sample is irradiated with electromagnetic energy from the infrared region of the electromagnetic spectrum (wavelength ~0.7–500 mm). The sample is irradiated with all infrared wavelengths simultaneously, and mathematical manipulation of the Fourier transform is used to produce the absorption spectrum or "fingerprint" of the material. Molecular absorptions in the infrared region are due to rotational and vibrational motion in molecular bonds, such as stretching and bending. The technique is commonly used for the identification of plastics, additives, and coatings. Also called FTIR.

fractional melt index resin—Thermoplastics having a low melt index of <1. These resins have higher molecular weights and are harder to extrude because of lower rate and greater force requirements compared to the lower molecular weight resins. They are mainly used for heavy duty applications such as pipe.

free surface energy—See *surface tension*.

frequency—The number or cycles completed by a periodic quantity in a unit time.

friction—Force parallel to and resisting motion between two surfaces under pressure.

friction stir welding—A friction welding technique where the heat is generated by a rotating tool or vibrating blade within the joint. Also called FSW.

friction welding—Welding methods for thermoplastics in which friction provides the heat necessary to melt the parts at the joint interface. Friction welding methods include spin welding, vibration welding, orbital welding, and ultrasonic welding.

FSW—See *friction stir welding*.

FTIR—See *Fourier transform infrared spectroscopy*.

fusion bonding—See *heated tool welding*.

G

gain—In ultrasonic welding, the ratio of output amplitude to input amplitude of a horn or booster. See also *booster, horn*.

gamma radiation—Ionizing radiation propagated by high-energy protons (e.g., emitted by a nucleus in transition between two energy levels).

general purpose polystyrene—Amorphous thermoplastic prepared by homopolymerization of styrene. It has good tensile and flexural strengths, high light transmission and adequate resistance to water, detergents and inorganic chemicals. It is attached by hydrocarbons and has a relatively low impact resistance. Processed by injection molding and foam extrusion. Used to manufacture containers, healthcare items such as pipettes, kitchen and bathroom housewares, stereo and camera parts and foam sheets for food packaging. Also called crystal polystyrene, crystal PS, GPPS.

generator—An electronic device that converts standard 120/240 volt, 50/60 Hz line voltage into high-frequency electrical energy.

glass fiber—Large family of short (staple, chopped, milled) or continuous fiber reinforcement, used widely in both thermosets and thermoplastics for increased strength, dimensional stability, thermal stability, corrosion resistance, and dielectric properties. The fibers are made by the melt drawing of various grades (electric, chemical, high tensile strength) of glass and are comprised of strands of filaments (roving) that can be further processed by size reduction, twisting, or weaving into fabrics or mats. Used in molding compounds, sprayup processes, die molding, layup, and other lamination processes. Glass fibers are often surface modified (e.g., with coupling agents) to improve bonding with polymer matrix or to impart special properties such as electrical conductivity (by coating with nickel). Also called glass roving.

glass filler—Widely used family of fillers in the form of beads, hollow spheres, flakes, or milled particles. They increase dimensional stability, chemical resistance, moisture resistance, and thermal stability of plastics.

glass mat reinforced thermoplastic—A composite sheet material based on a thermoplastic reinforced with a glass mat. The sheets are compression molded into stiff shapes. Also called GMT.

glass roving—See *glass fiber*.

glycol—See *ethylene glycol*.

glycol chlorohydrin—See *ethylene chlorohydrin*.

glycol modified PET—See *glycol modified polyethylene terephthalate*.

glycol modified polycyclohexylenedimethylene terephthalate—Thermoplastic polyester comprising a glycol, cyclohexylenedimethanol, terephthalic acid terpolymer. It exhibits excellent physical properties, chemical resistance and clarity. It has notched Izod strength comparable to that of polycarbonate. PCTG can be injection molded and film, sheet and tube extruded. It is often alloyed with polycarbonate or filled with glass fibers or mica. Also called PCTG.

glycol modified polyethylene terephthalate—Thermoplastic polyester prepared by polycondensation of cyclohexylenedimethylenediol, ethylene glycol, and terephthalic acid. Processed by injection and blow molding and shape, tubing, film and sheet extrusion. It is an amorphous, clear polymer having high stiffness and hardness and good toughness even at low temperatures. It is FDA approved. Applications include containers for cosmetics and foods, packaging film, medical devices, instrument covers, machine guards, and toys. Also called glycol modified PET, PETG, polycyclohexylenedimethylene ethylene terephthalate.

GMT—See *glass mat reinforced thermoplastic*.

GPPS—See *general purpose polystyrene*.

graphite fiber—See *carbon fiber*.

graphite filler—A crystalline form of carbon in powder form. Graphite occurs naturally and also is produced by heating petroleum coke, carbon black, and organic materials. Used as a lubricating filler for nylons and fluoropolymers. Also called black lead, carbon graphite, graphite powder, plumbago, powdered graphite.

graphite powder—See *graphite filler*.

grazing—See *cracking*.

hard clays—Sedimentary rocks composed mainly of fine clay mineral material without natural plasticity, or any compacted or indurated clay.

H

HAZ—See *heat affected zone*.

haze—The percentage of transmitted light which, in passing through a plastic specimen, deviates from the incident beam via forward scattering more that 2.5 degrees on average (ASTM D883).

HDPE—See *high density polyethylene*.

HDT—See *heat deflection temperature*.

heat affected zone—In welding, the region of the part that is affected by heat used to melt the joining surface. Microstructure of the heat affected zone is an important determinant of the quality of the weld. Also called HAZ.

heat deflection temperature—The temperature at which a material specimen (standard bar) is deflected by a certain degree under a specified load. Also called tensile heat distortion temperature, heat distortion temperature, HDT, deflection temperature under load.

heat distortion temperature—See *heat deflection temperature*.

heat seal temperature—Temperature required to join two or more films or sheets in contact by fusion.

heat sealing—A method of joining plastic films by the simultaneous application of heat and pressure to the areas in contact.

heat stability—See *thermal stability*.

heated tool welding—A method for joining thermoplastic parts in which the parts are pressed directly against a hot plate or heated tool. Part surfaces are heated until the melting or glass transition temperature is reached. The heated tool is then removed and the parts are pressed together until cooled. The heated tool can be coated with polytetrafluoroethylene to reduce melt sticking. A heated plate is used for flat surfaces and a heated tool in the shape of the joint for irregularly shaped surfaces. Also called butt fusion welding, direct contact heated tool welding, fusion bonding, hot plate welding, hot shoe welding, hot tool welding.

hermetic seal—A seal or weld that is impervious to liquids and air and other gases; airtight .

hexalhydrobenzene—See *cyclohexane*.

hexamethylene—See *cyclohexane*.

hexamethylenediamine sebacic acid polymer—See *nylon 610*.

hexanaphthene—See *cyclohexane*.

HF welding—See *radio frequency welding*.

high density polyethylene—A linear polyethylene with density 0.94–0.97 g/cm^3, molecular weight 50,000–250,000, and high crystallinity. Produced by co- or homopolymerization in a slurry or gas phase at relatively low pressure and temperature. High density polyethylene has excellent low temperature toughness, chemical resistance, good dielectric properties, and relatively high softening temperatures, but poor weatherability. The properties improve with decreasing polydispersity. Processed by extrusion, blow molding, injection molding, rotational molding, and powder coating. Used as films and coatings and in housewares, containers, food packaging, liners, cable insulation, profiles, pipes, bottles, and toys. Also called HDPE, PE-HD.

high frequency welding—See *radio frequency welding*.

high impact polystyrene—See *impact polystyrene*.

high molecular weight low density polyethylene—-Thermoplastic polyolefin with improved environmental stress crack resistance, impact strength and abrasion resistance but reduced flow processibility and tensile strength. Also called HMWLDPE.

high performance fusion welding—A flash free welding technique for thermoplastic pipes which uses an electrofusion-type fitting on the outside of the joint and an inflated bladder on the inside to constrain the melt during welding. Also called HPF welding. See also *flash free welding*.

HIPS—See *impact polystyrene*.

HMWLDPE—See *high molecular weight low density polyethylene*.

hold time—In welding, the length of time allotted for the melted plastic to solidify. In process engineering, the residence time of an individual ingredients in a reaction vessel or other processing apparatus. Also called holding time.

holding load—In mechanical fastening, the load required in tensile tests to pull an insert or screw out of the surrounding plastic.

holding time—See *hold time*.

hoop stress—The tensile or circumferential stress in the wall of a material of cylindrical form subjected to internal or external pressure.

horn—In ultrasonic welding, an acoustical tool designed to transfer mechanical vibrations from the transducer-booster assembly directly to the parts to be assembled. Also called sonotrode. See also *coupler*.

hot air welding—See *hot gas welding*.

hot bar welding—A method for joining thermoplastic films and thin sheets, where a heated bar is pressed against the films to be welded. See also *heat sealing*.

hot gas welding—A method for joining thermoplastic materials in which the parts are softened by hot gas, usually air, from a welding torch and joined together at the softened points. A filler rod composed of the same material as the parts is generally used to fill and consolidate the gap between the parts. Hot gas welding is used for joining and repair of thermoplastic parts and for lap welding of thin sheets. Also called hot air welding.

hot knife sealing—A joining process in which a heated tool in the form of a knife blade is passed between the parts being joined, so that heat is applied to the seal side of the parts. The blade is then removed, and surfaces are pressed together for a few seconds until the bond solidifies.

hot melt adhesive—An adhesive that is applied in a molten state which forms a bond after cooling to a solid state. Acquires adhesive strength through cooling, unlike adhesives that achieve strength through solvent evaporation or chemical cure.

hot plate welding—See *heated tool welding*.

hot shoe welding—See *heated tool welding*.

hot tack strength—The force required to separate a molten seal in heat-sealable thermoplastic films. It determines the rate at which the film can be sealed.

hot tool welding—See *heated tool welding*.

HPF welding—See *high performance fusion welding*.

hydraulic—Fluid powered, operated, or controlled.

hydrophilic surface—Surface of a hydrophilic substance that has a strong ability to bind, adsorb or absorb water; a surface that is readily wettable with water. Hydrophilic substances include carbohydrates such as starch.

hydroxy group—See *hydroxyl group*.

hydroxyl group—A combination of one atom of hydrogen and one atom of oxygen, -OH, attached by a single covalent bond to another atom, such as carbon, in a molecule of an organic or inorganic substance. It is a characteristic group of alcohols and hydroxides. Hydroxyl groups on the surface of a material usually make it hydrophilic. Hydroxyl groups are quite reactive (e.g., they readily undergo etherification or esterification). Also called hydroxy group.

I

impact energy—The energy required to break a specimen, equal to the difference between the energy in the striking member of the impact apparatus at the instant of impact and the energy remaining after complete fracture of the specimen. Also called impact strength.

impact polystyrene—Thermoplastic produced by modifying PS with rubber such as butadiene rubber or with butadiene copolymers. Impact PS has good dimensional stability, high rigidity, and good low temperature impact strength, but poor barrier properties, grease resistance, and heat resistance. Processed by extrusion, injection molding, thermoforming, and structural foam molding. Used widely in food packaging, kitchen housewares, toys, small appliances, personal care items, and audio cassettes. Also called high impact polystyrene, HIPS, IPS, styrene rubber plastic.

impact strength—See *impact energy*.

impedance transformer—See *booster*.

impulse welding—A method for joining thermoplastic films and thin sheets, where the films are placed between two jaws, at least one of which contains a resistance wire strip. In this technique, both the heating and cooling stages are carried out under pressure. See also *heat sealing*.

induction welding—A technique used for joining plastics and other materials. High frequency, electromagnetic energy is used to excite molecules of a ferromagnetic material placed at the joint interface. The heat generated melts the surrounding thermoplastic matrix, fusing the two parts together. Also called electromagnetic welding, EMA welding, magnetic induction welding.

inertia—Property by which matter continues in a state of rest or motion unless acted on by external force.

inertia welding—Method of spin welding in which the rotating tool is driven up to the required speed before welding and then not driven during welding.

infrared welding—A welding technique in which infrared radiation is used to heat the surfaces of thermoplastic parts to the melting temperature. Infrared radiation pertains to the region of the electromagnetic spectrum between visible light and radar. Wavelengths of from 1 to 15 µm (0.00004–0.0006 inches) are used in infrared welding.

initial tear resistance—The force required to initiate tearing of a flexible plastic film or thin sheeting at very low rates of loading, measured as maximum stress usually found at the onset of tearing.

injection molding—Method of mass production for plastics components, which utilizes pressurized flow of molten plastic into a shaped former.

injection welding—A variant of extrusion welding, where molten thermoplastic is injected into the joint, rather than extruded.

insert—In mechanical fastening, an integral part of a plastic molding consisting of a metal, plastic, or other material that can be molded into the plastic or pressed into position after molding.

interference fit—A mechanical fastening method used to join two parts, such as a hub and a shaft, in which the external diameter of the shaft is larger than the internal diameter of the hub. This interference produces high stress in the material and must be determined carefully to avoid exceeding the allowable stress for the material. Stress relaxation can occur in interference fits, causing the joint to loosen over time. Also called press fit.

internal friction—Conversion of mechanical strain energy to heat in a material exposed to a fluctuating stress. See also *Coulombic friction*.

iodine treatment—In adhesive bonding, a surface preparation technique in which the surface crystallinity of the polymer is changed from the alpha form, in which N-H groups are parallel to the surface, to the beta form, in which the N-H functional groups are perpendicular to the surface. Commonly used for nylon, iodine treatment increases the reactivity of the surface but is not believed to provide sites for mechanical interlocking.

ionizing radiation dose—See *radiation dose*.

ionomer—Thermoplastic containing pendant ionized acid groups which create ionic crosslinks between chains. Usually, only <10% repeating units of ionomers contain ionized groups, whereas polyelectrolytes contain substantially more. A typical commercial representative of this group is ethylene methacrylic acid copolymer sodium salt. The ionomers offer high flex and impact toughness in the temperature range from –160°F (–107°C) to 180°F (82°C). They have excellent resistance to puncture and to organic solvents, mild acids and bases, and edible oils; high adhesion to paper and other substrates; and good dielectric properties. Many ionomers are FDA approved for food packaging. Some disadvantages of ionomers are poor weatherability, flammability, and high thermal expansion. Processed by injection, blow, and rotational molding; blown and cast film extrusion; and extrusion coating. Used in packaging, shoe soles, auto bumper guards, laminated bags, sporting goods, and foam sheets.

IPS—See *impact polystyrene*.

isocyanate resin—See *nonelastomeric thermosetting polyurethane*.

isophthalate polyester—A thermoset unsaturated polyester based on isophthalic anhydride. Also called isophthalic polyester.

isophthalic polyester—See *isophthalate polyester*.

Izod—See *Izod impact energy*.

Izod impact energy—The energy required to break a v-notched specimen equal to the difference between the energy in the striking member of the impact apparatus at the instant of impact with the specimen and the energy remaining after complete fracture of the specimen. It is measured according to ASTM D256. Also called Izod, Izod impact strength, Izod strength, Izod v notch impact strength, notched Izod impact strength, notched Izod strength.

Izod impact strength—See *Izod impact energy*.

Izod strength—See *Izod impact energy*.

Izod v notch impact strength—See *Izod impact energy*.

J

J—See *joule*.

jig—A device used to hold parts in place and guide the tool during assembly or machining operations.

joint design—Molding the shape of mating thermoplastic parts to achieve the intended assembly results.

joint efficiency—See *weld factor*.

joule—A unit of energy in SI system that is equal to the work done when the point of application of a force of one newton (N) is displaced through distance of one meter (m) in the direction of the force. The dimension of joule is Nm. Also called J.

K

ketohexamethylene—See *cyclohexanone*.

ketone resin—See *polyketone*.

kinetic energy—The energy contained in a object by virtue of its motion.

kinetic coefficient of friction—The ratio of tangential force, which is required to sustain motion without acceleration of one surface with respect to another, to the normal force, which presses the two surfaces together.

L

lamella—In plastics, the basic morphological unit of a crystalline polymer. Shaped like a thin plate or ribbon, approximately 10 nm thick.

lap joint—A joint in which one adherend is placed partly over the other adherend; overlapped areas are bonded together.

lap shear test—See *ASTM D1002*.

laser—A device used to produce an intense light beam with a narrow band width. Laser is an acronym for light amplification by stimulated emission of radiation.

laser welding—A joining method for thermoplastics in which a high intensity laser beam is used to generate heat at the part surfaces, causing the materials to melt and coalesce.

LCP—See *liquid crystal polymer*.

LDPE—See *low density polyethylene*.

LIM—See *reaction injection molding system*.

LIM system—See *reaction injection molding system*.

linear friction welding—See *vibration welding*.

linear low density polyethylene—Linear carbon-chain copolymers of ethylene with higher alfa-olefins such as 1-butene and 1-hexene, having density 0.91–0.94 g/cm^3. They are prepared by solution or gas-phase copolymerization. LLDPE has better tensile, tear, and impact strength and crack resistance properties, but poorer haze and gloss than those of low density polyethylene. LLDPE is processed by extrusion, which requires increased pressure and higher melt temperatures than low density polyethylene, and molding. Used as films and sheets and in pipes, electrical insulation, liners, bags, and food wraps. Also called LLDPE.

linear polyethylenes—Polyolefins with linear carbon chains. Linear polyethylenes are stiff, tough and have good resistance to environmental cracking and low temperatures. Processed by extrusion and molding. Used to manufacture film, bags, containers, liners, profiles and pipe. See also *high density polyethylene, linear low density polyethylene*.

liquid crystal polyester—See *liquid crystal polymer*.

liquid crystal polymer—Thermoplastics comprised of highly aromatic copolyesters with a highly ordered structure in both melt and solid states. They have very high tensile and flexural strengths at elevated temperatures and are resistant to all chemicals, weathering, radiation, and burning. Processed at high temperatures by sintering and injection molding. Used as ceramic and metal substitutions for electrical components, electronic devices, chemical process equipment, and parts for aerospace, transportation, and safety industry. Also called LCP, liquid crystalline polyester, liquid crystalline polymer, liquid crystal polyester.

liquid crystalline polyester—See *liquid crystal polymer*.

liquid crystalline polymer—See *liquid crystal polymer*.

liquid injection molding system—See *reaction injection molding system*.

LLDPE—See *linear low density polyethylene*.

locating pin—Protrusion in tooling which fits into an equivalent hole in the parts to be welded; used to maintain part position and to transfer movement to the part efficiently, in spin welding. Also called drive pin.

long glass fiber—See *continuous glass fiber*.

low density polyethylene—A branched carbon-chain polyethylene thermoplastic prepared by homopolymerization of ethylene under high pressure. Its density is 0.91–0.94 g/cm^3. It has high toughness, impact strength, flexibility, film transparency, chemical resistance, good dielectric properties, and low water permeability and brittleness temperature. It is susceptible to environmental stress cracking, weathering, and has poor thermal stability. Processed by extrusion coating, injection and blow molding, and film techniques; crosslinkable. Used in packaging and shrink films, bags, laminates, toys, bottle caps, cable insulation, and coatings. Also called LDPE.

M

magnetic induction welding—See *induction welding*.

manifold—Hollow component with several outlets (e.g., used to distribute air around an engine).

marking—In part assembly, the scuffing or marring of a plastic part, which detracts from its cosmetic appearance.

mass density—See *density*.

mass spectrometry—A method of substance structure analysis based on sending an ionized beam of substance molecules or molecular fragments through a magnetic field to achieve a separation depending on the mass-electric charge ratio of the particles.

maximum diametral interference—In interference fit design, the maximum allowable interference for a particular hub and shaft, per unit measurement of shaft diameter. The maximum diametral interference depends on the types of materials used in the hub and shaft and on the ratio of shaft diameter to hub outside diameter. It is determined to ensure that hoop stress in the interference fit does not exceed the allowable stress of materials used in the design.

MDPE—See *medium density polyethylene*.

mechanical fastening—A method of joining plastics and/or metals using fasteners such as machine screws, self-tapping screws, inserts, rivets, nuts and bolts, or by molding in interlocking configurations directly into the parts, such as in snap-fits.

mechanical properties—Properties describing the reaction of physical systems to stress and strain.

mechanical strain—See *strain*.

medium density polyethylene—Type of polyethylene defined by a density range of 0.926–0.940 g/cm^3. It therefore has a density lower than HDPE. MDPE can be produced by chromium/silica catalysts, Ziegler-Natta catalysts or metallocene catalysts. It is primarily used for pressure pipe applications. Also called MDPE.

medium glass fiber—See *chopped glass fiber*.

megarad—One rad is equivalent to an energy absorption per unit mass of 0.01 joule per kilogram of irradiated material; one megarad is 10^6 rads. Also called Mrad.

MEK—See *butanone*.

MEK peroxide—See *methyl ethyl ketone peroxide*.

melt flow index—See *melt index*.

melt flow rate—See *melt index*.

melt index—The amount, in grams, of a thermoplastic polymer that can be forced through an orifice of 0.0825 inches (2.1 mm) diameter when subjected to a force of 2.16 kgf (4.76 lbf) in 10 minutes at 190°C (374°F). The test is performed using an extrusion rheometer as described in ASTM D1238. Also called base resin melt index, melt flow index, melt flow rate, MFI, MFR, MI.

methanol—See *methyl alcohol*.

methyl acrylate ethylene polymer—See *ethylene methyl acrylate copolymer*.

methyl alcohol—An aliphatic alcohol, CH_3OH. A colorless, volatile, flammable liquid. Autoignition point is 464°C (867°F). Toxic by ingestion. Derived by catalytic hydrogenation of carbon monoxide, oxidation of natural gas, or gasification of wood. Used as a fuel, as a solvent for cellulosic and other resins, and in organic synthesis for the manufacture of formaldehyde and proteins. Also called methanol.

methylbenzene—See *toluene*.

methylene chloride—See *dichloromethane*.

methyl ethyl ketone—See *butanone*.

methyl ethyl ketone peroxide—($C_8H_{16}O_4$) A colorless liquid. A strong oxidizing agent and irritant to skin and tissue. Its TLV is 0.2 ppm in air (ceiling level). Fire hazard in contact with organic materials. Used as a hardening agent for fiber glass reinforced plastics and in the manufacture of acrylic resins. Also called ethyl methyl ketone peroxide, MEK peroxide.

methyl methacrylate—($CH_2{:}C(CH_3)COOCH_3$) A colorless, volatile liquid; melts at –48.2°C (–54.8°F) and boils at 101°C (214°F). Soluble in most organic solvents; slightly soluble in water. Easily polymerized by light, heat, ionizing radiation and chemical catalysts; can be copolymerized by other methacrylate esters or other monomers. Its TLV is 100 ppm in air. It is flammable; explosive limit in air is 2.1–12.5%. Derived from oxidation of tert-butyl alcohol first to methacrolein then to methacrylic acid, followed by reaction with methanol, or from reaction of methanol, acetone cyanohydrin and dilute sulfuric acid. Used as a monomer for polymethyl methacrylate and acrylic resins.

methyl methacrylate-butadiene-styrene terpolymer—A thermoplastic comprising a polymer of methyl methacrylate, butadiene and styrene. Also called butadiene-styrene-methyl methacrylate polymer, styrene-butadiene-methyl methacrylate polymer, styrene-methyl methacrylate-butadiene polymer.

methyl methacrylate terpolymer—A thermoplastic comprising a polymer of methyl methacrylate with two other unsaturated monomers. Also called MMA terpolymer.

methylene chloride—See *dichloromethane*.

methylene dichloride—See *dichloromethane*.

methylphenylpolysiloxane—See *methylphenylsilicone*.

methylphenylsilicone—Thermosetting elastomer comprised of a siloxane backbone with pendant phenyl and methyl groups. The presence of phenyl groups improves high temperature resistance, oxidation properties, radiation resistance, and compatibility with organic materials. It may be used as a plastics additive or as a flow control agent in polyester coatings. Also called methylphenylpolysiloxane.

methylpolysiloxane—See *methylsilicone*.

methylsilicone—Thermosetting elastomer comprised of a siloxane backbone with pendant methyl groups. It is characterized by excellent thermal stability and good resistance to oxidation. Uses include electrical insulation, heat-resistant paints and varnishes, and protective and decorative finishes. Also called methylpolysiloxane.

methylvinylfluoropolysiloxane—See *methylvinylfluorosilicone*.

methylvinylfluorosilicone—Thermosetting elastomer comprised of a siloxane backbone with pendant vinyl, methyl, and fluorine groups. Because of the presence of the vinyl group it may be vulcanized to high degrees of crosslinking. It is commonly used in applications where high or low temperatures are encountered and where resistance to fuels or oils is required. Also called methylvinylfluoropolysiloxane.

methylvinylpolysiloxane—See *methylvinylsilicone*.

methylvinylsilicone—Thermosetting elastomer comprised of a siloxane backbone with pendant methyl and vinyl groups. Because of the presence of the vinyl group it can be vulcanized to high degrees of crosslinking. It is generally used in sealants, encapsulants, coatings in construction, automotive cables, gaskets, vending machine tubing, pressure-sensitive adhesives, electrical insulating tapes, and masking tapes. Also called methylvinylpolysiloxane.

methylvinylsilicone methylvinylfluorosilicone alloy—Thermosetting elastomer comprising an alloy of methylvinylsilicone and methylvinylfluorosilicone.

MFI—See *melt index*.

MFR—See *melt index*.

MI—See *melt index*.

micron—A unit of length equal to 10^{-6} meter. Its symbol is Greek small letter mu.

microwave welding—A welding technique in which high frequency electromagnetic radiation, usually 2–10 GHz, is used to heat a susceptor material placed at the joint interface. Heat conduction from the susceptor to the joint interface melts the thermoplastic parts, forming a weld after cooling.

microprocessor controlled—Equipment incorporating a computer to control the welding parameters.

migration—A mass-transfer process in which the matter moves from one place to another usually in a slow and spontaneous fashion. In plastics and coatings, migration of pigments, fillers, plasticizers and other ingredients via diffusion or floating to the surface or through interface to other materials results in various defects called blooming, chalking, bronzing, flooding, bleeding, etc.

milled glass fiber—See *milled glass filler*.

milled glass filler—Fillers made by hammer milling continuous glass strands. Used as anticrazing reinforcing fillers for adhesives and in plastics. Also called milled glass fiber.

mineral filler—Large subclass of inorganic fillers comprised of ground rocks or natural or refined minerals. Some fillers, so-called commodity minerals, are relatively inexpensive and are used mostly as extenders. A good example of these is ground limestone. Other fillers, so-called specialty minerals, are usually reinforcing fillers. These are inherently small particle size fillers, such as talc, and surface chemically modified fillers.

MMA terpolymer—See *methyl methacrylate terpolymer*.

modified polyphenylene ether—See *modified polyphenylene oxide*.

modified polyphenylene oxide—Thermoplastic polyphenylene oxide alloys with polystyrene, usually high impact. The alloys have high impact strength and improved resistance to heat, fire, and chemicals, compared to polystyrene, but are attacked by organic solvents. Processed by injection molding, extrusion, and structural foam molding. Used in automotive parts, telecommunication devices, and appliances. Also called modified polyphenylene ether, modified PPE, modified PPO, MPO.

modified polyphenylene oxide nylon 6 alloy—Thermoplastic alloy of modified polyphenylene oxide and nylon 6.

modified polyphenylene ether—See *modified polyphenylene oxide*.

modified PPE—See *modified polyphenylene oxide*.

modified PPO—See *modified polyphenylene oxide*.

modulus of elasticity—The ratio of unit stress to the unit of deformation of an elastic material below the proportional limit. It gives an indication of a material's stiffness. Also called elasticity constant.

molded threaded fastener—A fastener or insert, usually metal, that is molded into a part during the molding process. The outside surface can be smooth, knurled, or grooved. The inside surface is threaded to allow insertion of a machine screw.

molded-in insert—A method of mechanical fastening in which an insert, usually metal, is molded into one of the parts to be joined. The insert is internally threaded to accept a machine screw, and knurls and grooves on the outer surface of the insert provide pull-out and rotation resistance. Molded-in inserts create high stress in the material around the insert.

molded-in thread—A mechanical assembly method in which internal or external threads are molded into plastic parts.

molecular weight—The molecular weight is the sum of the atomic weights of all the atoms in a molecule. Also called average molecular weight, formula weight, MW.

MPO—See *modified polyphenylene oxide*.

Mrad—See *megarad*.

multilayer film—A thermoplastic film consisting of two or more different or similar films joined together (e.g., by coextrusion or lamination) to attain special properties uncharacteristic for a conventional film.

MW—See *molecular weight*.

N

N,N-dimethylformamide—($HCON(CH_3)_2$) A water-white liquid that boils at 152.8°C (307.0°F). A dipolar, aprotic solvent miscible with water and organic solvents except for halogenated hydrocarbons. Its autoignition temperature is 445°C (833°F). Its TLV is 10 ppm in air; it is toxic by skin absorption. Derived from the reaction of methyl formate with dimethylamine. Used as a solvent for vinyl resins, acetylene, butadiene, and acid gases, in polyacrylic fibers, as a carrier for gases, and in organic synthesis. Also called DMF.

N-methyl-2-pyrrolidone—(C_5H_9NO) A colorless, combustible liquid with an amine-like odor that boils at 202°C (396°F). Soluble in water, castor oil, and various organic solvents. Derived by reaction of acetylene and formaldehyde under high pressure. Used as a solvent for petroleum, acetylene, and resins, a spinning agent for polyvinyl chloride, a pigment dispersant, and a chemical intermediate. Also called NMP.

nanometer—A unit of length equal to 10^{-9} meters. Often used to denote the wavelength of radiation, especially in UV and visible spectral region. Also called nm.

NBR—See *nitrile rubber*.

Nd:YAG laser—This uses a neodymium-doped yttrium aluminum garnet crystal as lasing medium. It is optically pumped using a flashlamp or laser diodes, and typically emits light with a wavelength of 1064 nm.

near field—Refers to the distance that ultrasonic energy is transmitted from the horn to the joint interface in ultrasonic welding. Near field welding occurs when the joint is 0.25 inches (6.4 mm) or less from the point at which the horn contacts the part. See also *far field*.

neoprene—See *neoprene rubber*.

neoprene rubber—Generic name for synthetic rubbers made from polymers of chloroprene. They are noted for their good resistance to oil, solvents, heat, sunlight, ozone, and weathering. Most types may be vulcanized to tough products without the use of sulfur. Also called chloroprene rubber, neoprene, polychloroprene.

nest—See *fixture*.

nitrile rubber—A synthetic rubber made by random polymerization of acrylonitrile with butadiene by free radical catalysis. The copolymers vary basically in butadiene-acrylonitrile ratios, and Mooney viscosities. Typical properties include tensile strength 1000–3000 psi (7–20 MPa), elongation 100% and maximum service temperature 121–148°C (250–298°F). In addition, they are resistant to oils, solvents, and greases, and to heat and abrasion. Common uses include oil-resistant applications, shoe soles, gaskets, fuel hose, packing oil seals, hydraulic equipment, and adhesives. Also called acrylonitrile butadiene rubber, acrylonitrile rubber, NBR.

nm—See *nanometer*.

NMP—See *N-methyl-2-pyrrolidone*.

nodal point—In ultrasonic welding, the point or points in a booster or horn where little or no linear motion occurs.

noncontact heated tool welding—A form of infrared welding in which parts are placed very near a heated tool but are not in direct contact with it. Heat is transferred to the part surfaces by radiation and convection. The heated tool is removed when melting occurs, and parts are then pressed together for cooling and solidification. Used for high temperature polymers when high melting temperatures prohibit the use of non-stick coatings on the heated tool surface. See also *direct contact heated tool welding, heated tool welding, infrared welding*.

nonelastomeric thermoplastic polyurethane—Polyisocyanate polyol polymers that are not chemically crosslinked. They have high abrasion resistance, good retention of properties at low temperatures, but poor heat resistance, weatherability, and resistance to solvents. Nonelastomeric PURs are flammable and are made with toxic substances (isocyanates). Processed by injection molding and extrusion. Also called rigid thermoplastic polyurethane, rigid thermoplastic urethane, RTPU, TPUR. See also *polyurethane*.

nonelastomeric thermosetting polyurethane—Urethane resins that are thermosets, comprised of polyisocyanate polyol prepolymers or monomer mixtures that can be cured at moderate or ambient temperatures in the presence of catalysts. The resins can be foamed. Cured resins have a wide range of properties including high abrasion resistance, good retention of properties at low temperatures, but poor heat resistance, weatherability, and resistance to solvents. The resins are flammable and are made with toxic substances (isocyanates). Processed by reaction injection molding, various foam techniques, casting, and coating. Used widely in heat insulation, machine parts, potting, encapsulation, electronic housings, and auto body panels and trim. Also called isocyanate resin, PUR, urethane, urethane resin. See also *polyurethane*.

nonpolar—In molecular structure, a molecule in which positive and negative electrical charges coincide. Most hydrocarbons, such as polyolefins, are nonpolar.

notch effect—The effect of the presence of specimen notch or its geometry on the outcome of a test such as an impact strength test of plastics. Notching results in local stresses and accelerates failure in both static and cycling testing (mechanical, ozone cracking, etc.).

notched Izod impact strength—See *Izod impact energy*.

notched Izod strength—See *Izod impact energy*.

nylon—Thermoplastic, mostly aliphatic polyamides prepared usually either by polymerization of dicarboxylic acid with diamine, or polymerization of amino acid, or ring opening polymerization of lactam. Nylons have good resistance to solvents, bases, and oils; to impact; abrasion; and creep. They have also high tensile strength and barrier properties, and a low coefficient of friction. Disadvantages include high moisture pickup, light degradation, and high mold shrinkage. Processing is achieved by injection, blow, and rotational molding; extrusion; and powder coating. Uses include automotive parts, electrical and electronic devices such as plugs, machine parts such as gears and pumps, housings for appliances and power tools, wire and cable jacketing, pipes, films, and fibers. See also *polyamide*.

nylon 11—An aliphatic polyamide thermoplastic prepared by polycondensation of 11-aminoundecanoic acid. It posesses good impact strength, hardness, and abrasion resistance. Very low water absorption of nylon 11 results in high dimensional stability. Other mechanical properties of nylon 11 are lower than those of most other nylons. The relatively low melting point of nylon 11 allows processing by powder coating and rotational molding in addition to extrusion and conventional molding. Uses include electric wire and cable insulation, tubing, mechanical parts, profiles, bearings, and coatings. Also called PA 11, polyamide 11, polyaminoundecanoic acid.

nylon 12—An aliphatic polyamide thermoplastic prepared by ring opening polycondensation of lauric lactam (azacyclotridecan-2-one). It has good impact strength, hardness, abrasion resistance, and dimensional stability. Its water absorption and specific gravity are the lowest among nylons. Other mechanical properties of nylon 12 are somewhat inferior. Nylon 12 can be processed by powder coating and rotational molding in addition to extrusion and conventional molding. Uses include sporting goods, automotive parts, and mechanical parts. Also called PA 12, polyamide 12, polyazacyclotridecanone.

nylon 46—Thermoplastic polyamide manufactured by the condensation of 1,4-butanediamine and adipic acid. Also called caprolactam pyrrolidone polymer, PA 46, polyamide 46, polytetramethyleneadipamide.

nylon 6—An aliphatic polyamide thermoplastic made by ring opening polycondensation of epsilon-caprolactam. The mechanical properties of nylon 6 are similar to those of nylon 66 but it picks up moisture more rapidly and loses strength more rapidly as moisture content and temperature increase. Nylon 6 has a lower melting point and is somewhat softer and less stiff than nylon 66. Nylon 6 has good weldability. It can be processed by injection, blow, and rotational molding and extrusion. Used for textile fibers, tire cord and molded articles such as machine parts. Also called PA 6, polyamide 6, polycaprolactam.

nylon 610—An aliphatic polyamide thermoplastic made by polycondensation of hexamethylenediamine with sebacic acid. It has a lower melting point and lower water absorption than nylon 66 or nylon 6. It retains stiffness and mechanical properties better when wet than does nylon 66. Processed by injection molding and extrusion. Used as monofilament in paint brushes. Also called hexamethylenediamine sebacic acid polymer, PA 610, polyamide 610, polyhexamethylene sebacamide.

nylon 612—An aliphatic polyamide thermoplastic made by polycondensation of 1,12-dodecanedioic acid with hexamethylenediamine. Nylon 612 has good dimensional stability and low moisture absorption. Its physical and mechanical properties remain stable through a wide humidity range. It is processed by injection molding and extrusion. Uses include wire jacketing, cable sheathing, packaging film, bristles, bushings, and housings. Also called dodecanedioic acid hexamethylenediamine polymer, PA 612, polyamide 612.

nylon 66—An aliphatic polyamide thermoplastic prepared by polycondensation of adipic acid with hexamethylenediamine. It exhibits high tensile strength, elasticity, toughness, and abrasion resistance. Nylon 66 has good solvent resistance but low weatherability and undergoes discoloration in air at elevated temperatures. Good mechanical properties are maintained up to 300°F (149°C). Moisture resistance of nylon 66 is fair; moisture acts as plasticizer, increasing flexibility and toughness of the polymer. It is processed by injection molding and extrusion. Major applications include textile fibers, self-lubricating bearing parts and gears, rollers and door latches in appliances. Electrical applications are restricted to wire jacketing, due to the ease of polarization. Also called adipic acid hexanediamine polymer, PA 66, polyamide 66, polyhexamethyleneadipamide.

nylon 666—An adipic acid-caprolactam-hexamethylenediamine polymer thermoplastic. Characterized by high strength, toughness, low friction coefficient, good abrasion and fatigue resistance, adequate dielectric properties, and relatively high moisture absorption and decreased dimentional stability. Processed by injection molding and extrusion. Used in transportation, electrical, and industrial applications. Also called PA 666, polyamide 666.

nylon 6/3T—An amorphous polyamide manufactured by the condensation of 50 mol% 1,4-benzenedicarboxylic acid, dimethyl ester and 50 mol% of an equimolar mixture of 2,2,4-trimethyl-1,6-hexanediamine and 2,4,4-trimethyl-1,6-hexanediamine. It is transparent and has low mold shrinkage, low tendency to warp and good chemical resistance. It is used in electrical engineering for high-voltage switch casings, battery seals and relay casings, and for liquid-level indicators and valve blocks. Also called PA 6/3T, polyamide 6/3T.

nylon MXD6—A poly-m-xylyleneadipamide thermoplastic with lower elongation at break than nylon 6 or 66, low melt viscosity, and good flexural strength and modulus. It resists alkalies and hydrolytic degradation. Also called PA MXD6, polyamide MXD6, polyxylyleneadipamide.

O

oil-canning—See *diaphragmming*.

olefinic plastic—See *polyolefin*.

olefinic resin—See *polyolefin*.

olefinic thermoplastic elastomer—Usually continuous blends of EPDM or EPR rubbers with polypropylene or polyethylene, which are sometimes crosslinked. They have low specific gravity, good resistance to weak acids and bases and to polar solvents, excellent dielectric properties, wide range of mechanical properties, and good (re)processability. The negatives include poor oil resistance and flammability. Blended materials have low compression set at elevated temperatures, whereas crosslinked materials have good compression set but cost more. Processed by extrusion, injection and blow molding, thermoforming, and calendering. Applications include automotive parts, building materials (e.g., weather stripping), wire and cable jacketing, and sporting goods. Also called olefinic thermoplastic rubber, olefinic TPE, polyolefin thermoplastic rubber, TEO, thermoplastic olefinic rubber, thermoplastic polyolefin rubber, TPO.

olefinic thermoplastic rubber—See *olefinic thermoplastic elastomer*.

olefinic TPE—See *olefinic thermoplastic elastomer*.

one-part adhesive—An adhesive that does not require a separate hardener or catalyst for bonding to occur. Types of one-part adhesive include UV curing, curing, emulsion, solvent, and water-activated. UV curing adhesives cure only by application of ultraviolet light; other curing one-part adhesives contain an integral catalyst or hardener with a degree of latency, so that cure at either room temperature or elevated temperature is possible. These curing adhesives must be refrigerated during storage and can have unpredictable curing behavior; examples are a liquid epoxy and dicyandiamide hardener, aerobic adhesives that require oxygen or moisture for activation, or silicone adhesives that require moisture. Emulsion adhesives are thermoplastics or elastomers dispersed in an aqueous phase, such as a copolymer of vinyl acetate and ethylene; one substrate must be permeable to allow escape of water from the system. Solvent adhesives are solutions or pastes of thermoplastics or elastomers in organic or water solvents. Water-activated adhesives, based on starch, cellulosics, or protein, are dry powders that must be mixed with water for activation; adhesive strength develops when the water is lost, so that usually one substrate must be permeable. See also *two-part adhesive*.

optical properties—The effects of a material or medium on light or other electromagnetic radiation passing through it, such as absorption, reflection, etc.

orbital welding—Process which uses repeating rotation of each point on the surface of one part around a different point on the surface of the other stationary part to create heating and melting at surfaces in contact and under pressure. See also *vibration welding*.

orientation—A process of drawing or stretching of as-spun synthetic fibers or hot thermoplastic films to orient polymer molecules in the direction of stretching. The fibers are drawn uniaxially and the films are stretched either uniaxially or biaxially (usually longitudinally or longitudinally and transversely, respectively). Oriented fibers and films have enhanced mechanical properties. The films will shrink in the direction of stretching when reheated to the temperature of stretching.

orthophthalate polyester—A thermoset unsaturated polyester based on o-phthalic anhydride. Also called orthophthalic polyester.

orthophthalic polyester—See *orthophthalate polyester*.

oven stability—See *thermal stability*.

overwelding—Welding procedure producing excessive heating at the joint, normally leading to excessive flash generation.

oxirane—See *ethylene oxide*.

P

PA—See *polyamide*.

Pa—See *pascal*.

PA 11—See *nylon 11*.

PA 12—See *nylon 12*.

PA 46—See *nylon 46*.

PA 6—See *nylon 6*.

PA 610—See *nylon 610*.

PA 612—See *nylon 612*.

PA 66—See *nylon 66*.

PA 666—See *nylon 666*.

PA6/3T—See *nylon 6/3T*.

PABM—See *polyaminobismaleimide*.

PAI—See *polyamide-imide*.

PANI—See *polyaniline*.

PARA—See *polyarylamide*.

parent material—Unwelded component material.

particulate filler—A material in the form of small particles added to a plastic to alter its physical, mechanical, thermal, electrical, or other properties or to decrease cost. Sometimes used to refer to mineral but not glass particles.

part shrinkage—Reduction in component size (e.g., during solidification) after molding or welding.

parts per hundred—A relative unit of concentration, parts of one substance per 100 parts of another. Parts can be measured by weight, volume, count or any other suitable unit of measure. Used often to denote composition of a blend or mixture, such as plastic, in terms of the parts of a minor ingredient, such as plasticizer, per 100 parts of a major, such as resin.

parts per hundred million—A relative unit of concentration, parts of one substance per 100 million parts of another. Parts can be measured by weight, volume, count or any other suitable unit of measure. Used often to denote very small concentration of a substance, such as impurity or toxin, in a medium, such as air. Also called pphm.

parts per million—A unit for measuring small concentrations of a material or substance as the number of its parts (arbitrary quantity) per million parts of a medium consisting of another material or substance.

parylene—Thermoplastics made by vapor-phase polymerization of p-xylene. Hot p-xylene vapors are cooled to condense the monomer and deposit it as a polymer in the form of a thin, uniform coating on a substrate such as paper or fabric.

pascal—An SI unit of measurement of pressure resulting from a force of one newton acting uniformly over an area of one square meter. Used to denote the pressure of gases, vapors or liquids and the strength of solids. Also called Pa.

PBI—See *polybenzimidazole*.

PBT—See *polybutylene terephthalate*.

PBTR—See *polybutylene terephthalate*.

PC—See *polycarbonate*.

PCM—See *polymer coated material joining*.

PCT—See *polycyclohexylenedimethylene terephthalate*.

PCTFE—See *polychlorotrifluoroethylene*.

PCTG—See *glycol modified polycyclohexylenedimethylene terephthalate*.

PDAP—See *diallyl phthalate*.

PDMS—See *polydimethylsiloxane*.

PE—See *polyethylene*.

PEEK—See *polyetheretherketone*.

PE-HD—See *high density polyethylene*.

PEI—See *polyetherimide*.

PEK—See *polyetherketone*.

PEKEKK—See *polyetherketoneetherketoneketone*.

PEKK—See *polyetherketoneketone*.

PEN—See *polyethylene naphthalate*.

perchloromethane—See *carbon tetrachloride*.

perfluoroalkoxy resin—Thermoplastic formed by polymerization of perfluoroalkoxyethylene. The material has higher temperature limit (500°F; 260°C) than fluorinated ethylene propylene copolymer and is similar to polytetrafluoroethylene in chemical resistance. It has low compressive and tensile strengths, but its creep resistance is superior to other fluoropolymers. Processed readily by molding, extrusion, rotational molding, and powder coating. Used as films, coatings, pipes, containers, and linings for chemical apparatus. Also called perfluoroalkoxyalkane, PFA, polyperfluoroalkoxyethylene.

perfluoroalkoxyalkane—See *perfluoroalkoxy resin*.

permittivity loss factor—See *dielectric dissipation factor*.

PES—See *polyethersulfone*.

PET—See *polyethylene terephthalate*.

PETE—See *polyethylene terephthalate*.

PETG—See *glycol modified polyethylene terephthalate*.

PEX—See *crosslinked polyethylene*.

PF—See *phenolic resin*.

PFA—See *perfluoroalkoxy resin*.

phenol formaldehyde resin—See *phenolic resin*.

phenolic—See *phenolic resin*.

phenolic resin—Thermoset phenolics are prepared by reacting phenols with excess or less than the stoichiometric amount of aldehydes such as formaldehyde in the presence of base or acid catalysts to give resole or novolak resins, respectively. The resins are soluble and heat curable. Novolak resins require a bifunctional crosslinking agent, usually diamine, to cure. Uncured or partially cured resins are used as coatings, adhesives, potting compounds, and binders. Cured resins are characterized by good dielectric properties, hardness, thermal stability, rigidity, and compressive strength but poor resistance to bases and oxidizers and dark color. Filled or reinforced phenolic powders can be processed by compression, transfer, or injection molding and extrusion. Molding uses include handles, electrical devices, and automotive parts. Also called PF, phenol formaldehyde resin, phenolic.

phenylethylene—See *styrene*.

phenylmethane—See *toluene*.

physical adsorption—See *adsorption*.

PI—See *polyimide*.

piezoelectric material—A material, such as ceramic, that changes dimensions when a voltage is applied, or produces voltage (electrical potential) when deformed. Used to convert mechanical energy into electrical energy and vice versa.

pimelic ketone—See *cyclohexanone*.

pitch diameter—The average between the major (outside) and minor (root) diameter of a thread. For practical purposes, this diameter is assumed to be equal to the diameter of the smooth shaft prior to threading.

PLA—See *polylactic acid*.

plasma arc treatment—A method for treating the surfaces of parts prior to solvent or adhesive bonding, in which an electrical current between two electrodes in a gas at low pressure excites the gas particles, producing free radicals. Contaminants are stripped from the surface of the part, and wettability is increased by reduction of the contact angle. Also called plasma discharge, plasma treatment. See also *corona discharge treatment*.

plasma discharge—See *plasma arc treatment*.

plasma treatment—See *plasma arc treatment*.

plastic—The general term for a wide range of synthetic or natural polymerization products. They are composed of organic condensation or addition polymers and may contain other substances to improve performance or economics. See also *polymer*.

plasticizer—A substance incorporated into a material such as plastic or rubber to increase its softness, processability and flexibility via solvent or lubricating action or by lowering its molecular weight. Plasticizers can lower melt viscosity, improve flow and increase low-temperature resilience of material. Most plasticizers are nonvolatile organic liquids or low-melting-point solids, such as dioctyl phthalate or stearic acid. They have to be non-bleeding, nontoxic and compatible with the material. Sometimes plasticizers play a dual role as stabilizers or crosslinkers.

plumbago—See *graphite filler*.

PMMA—See *polymethyl methacrylate*.

PMP—See *polymethylpentene*.

pneumatic—Air-powered, operated, or controlled.

polar—In molecular structure, a molecule in which the positive and negative electrical charges are permanently separated. Polar molecules ionize in solution and impart electrical conductivity to the solution. Water, alcohol, and sulfuric acid are polar molecules; carboxyl and hydroxyl are polar functional groups.

polyacrylate—See *acrylic resin*.

polyallomer—Crystalline thermoplastic block copolymers of ethylene, propylene, and sometimes other unsaturated monomers. Produced by anionic coordination polymerization. Have high impact strength, low density, and flex life.

polyamide—Thermoplastic polymers prepared usually by either polymerization of dicarboxylic acid with diamine, or polymerization of amino acid, or ring opening polymerization of lactam. Polyamides are characterized by the presence of backbone amide groups and can be aromatic (aramids) or aliphatic (nylons). Characterized by outstanding mechanical properties, chemical resistance, and antifriction properties. Processed by extrusion and molding. Used as reinforcement and textile fibers, machine parts, and coatings. Also called PA, polyamide plastic, polyamide resin. See also *aromatic polyamide, nylon*.

polyamide 11—See *nylon 11*.

polyamide 12—See *nylon 12*.

polyamide 46—See *nylon 46*.

polyamide 6—See *nylon 6*.

polyamide 610—See *nylon 610*.

polyamide 612—See *nylon 612*.

polyamide 66—See *nylon 66*.

polyamide 666—See *nylon 666*.

polyamide 6/3T—See *nylon 6/3T*.

polyamide plastic—See *polyamide*.

polyamide polyimide—See *polyamide-imide*.

polyamide resin—See *polyamide*.

polyamide thermoplastic elastomer—These thermoplastic elastomers are mostly copolymers containing soft polyether and hard polyamide blocks. They have improved chemical, abrasion, and thermal resistance and good impact strength and elongation. Processed by extrusion and injection and blow molding. Used in sporting goods, automotive and electrical applications, brushes, and bellows. Also called polyamide thermoplastic rubber, polyamide TPE, thermoplastic polyamide rubber.

polyamide thermoplastic rubber—See *polyamide thermoplastic elastomer*.

polyamide TPE—See *polyamide thermoplastic elastomer*.

polyamide-imide—A thermoplastic, normally made in a two step process by polymerizing trimellitic anhydride with an aromatic diamine to form a polyamic acid containing amide groups in the backbone and pendant carboxyl groups, followed by cyclocondensation of carboxyl and amide groups to form imide groups. They are characterized by superior tensile and compressive strengths at temperatures up to 500°F (260°C) with good dimensional stability and creep, impact, and chemical resistance. The high thermal stability of polyamide-imide is complemented by low flammability and good adhesive, dielectric, and barrier properties. On the other hand, polyamide-imides have poor processibility, due to their high viscoelastic behavior in the melt, and poor resistance to alkalis. Processing is achieved by compression and injection molding, and various powder sintering, film casting and solution coating techniques. Uses include jet engine components, washers, seal rings, bearings and joints in the automotive industry, and non-stick coatings. Also called amideimide resin, PAI.

polyaminobismaleimide—Thermosets derived from aromatic diamines and bismaleimides. May be cast and compression or transfer molded. High percentages of fillers may be incorporated. PABMs possess flow properties comparable to common thermosetting resins and thermochemical properties exceeding those of some light alloys. They are also flame- and radiation-resistant. They may be used for aircraft, electrical/electronic, friction, and ablation applications. Also called PABM.

polyaminoundecanoic acid—See *nylon 11*.

polyaniline—A family of polymers that exists in three different oxidation states at the molecular level: leucoemeraldine (fully reduced), emeraldine (half-oxidized), and pernigraniline (fully oxidized). The polyaniline emeraldine base becomes electrically conductive when doped with aqueous protonic acids, such as HCl. Conductivity is dependent on the morphology of the polyaniline. For high conductivity, polyaniline is spun into fibers with high crystallinity and orientation. Also called PANI.

polyaryl ether—See *polyphenylene oxide*.

polyaryl oxide—See *polyphenylene oxide*.

polyarylamide—Thermoplastic aromatic polyamide prepared by polymerization of aromatic diamine and aromatic diacid or its derivatives (e.g., anhydride). These plastics are characterized by high heat resistance, good retention of mechanical and dielectric properties at elevated temperatures, good dielectric properties, chemical resistance, high stiffness, and low flammability. High crystallinity results in good mechanical properties such as impact strength. Resistance to light is somewhat low. Processing is difficult because of its high melting point. Processed by solution casting, molding, and extrusion. Uses include film, fibers, and molded parts requiring good surface finish. Also called PARA.

polyarylate—See *aromatic polyester*.

polyarylene ether—See *polyphenylene oxide*.

polyarylene oxide—See *polyphenylene oxide*.

polyarylsulfone—A thermoplastic containing repeating sulfone and ether groups in its wholly aromatic backbone. It has excellent resistance to high and low temperatures, good impact strength, improved resistance to environmental stress cracking, good dielectric properties, rigidity, and resistance to acids and alkalies. Polyarylsulfone is nonflammable, but is attacked by some organic solvents. Processed by injection molding, compression molding, and extrusion. Used in high temperature electrical and electronic applications such as circuit boards and lamp housings, piping, and auto parts.

polyazacyclotridecanone—See *nylon 12*.

polybenzimidazole—Produced from the condensation of 3,3’,4,4’-tetraaminonbiphenyl (diaminobenzidine) and diphenyl isophthalate. It is characterized by a high degree of thermal and chemical stability. PBIs are dark brown in color and are used in applications requiring fibers with resistance to high temperatures and flame. Typical uses have been in the aerospace field, as protective coatings and reinforced laminates. Also called PBI.

polybutylene terephthalate—A saturated polyester thermoplastic prepared by transesterification of dimethyl terephthalate with butanediol during melt polycondensation. PBT has good tensile strength, dielectric properties, and chemical resistance, except for resistance to strong bases and halogenated solvents. Water absorption of PBT is very low. The material has a relatively low Izod impact strength and thermal stability, but these can be easily overcome by proper modification. Processed by injection and blow molding, extrusion, and thermoforming. Used in automotive body parts, electrical switches and relays, household appliances, and housings for power tools and various consumer products. Also called PBT, PBTR, polytetramethylene terephthalate.

polycaprolactam—See *nylon 6*.

polycarbodiimide—Polymers containing -N=C=N- linkages in the main chain, typically formed by catalyzed polycondensation of polyisocyanates. They are used to prepare open-celled foams with superior thermal stability. Sterically hindered polycarbodiimides are used as hydrolytic stabilizers for polyester-based urethane elastomers.

polycarbonate—Thermoplastic prepared by either phosgenation of dihydric phenols such as bisphenol A or by ester exchange between diaryl carbonate, usually diphenyl carbonate, and dihydric phenol. They are characterized by the presence of repeating carbonyldioxy groups in the backbone, but classified by some as polyesters. They have very good mechanical properties, especially impact strength, low moisture absorption, and good thermal and oxidative stability. They are self-extinguishing and some grades are transparent; but are attacked by strong acids and bases, soluble in organic solvents, and subject to stress cracking. Processed by injection and blow molding, extrusion, thermoforming, but require high processing temperatures. Used in telephone parts, dentures, business machine housings, safety equipment, nonstaining dinnerware, and food packaging. Also called PC.

polycarbonate polyester alloy—Thermoplastic alloy of polycarbonate and polyester. The impact-modified and filled grades available are suitable for injection and blow molding. Uses include automotive parts.

polychloroprene—See *neoprene rubber*.

polychlorotrifluoroethylene—Thermoplastic prepared by radical polymerization of chlorotrifluoroethylene. It has good transparency and great barrier properties. Dielectric properties and resistance to solvents, especially chlorinated, of CTFE are somewhat lower than those of perfluoropolymers, but tensile strength and creep resistance are higher. Processing is difficult, because of high melt viscosity, but possible by extrusion, injection molding, compression molding, and coating. Uses include chemical apparatus, cryogenic seals, films, and coatings. Also, CTFE spheres are used as fillers and CTFE oil is used as a lubricant in various plastics. Also called CTFE, PCTFE.

polycyclohexylenedimethylene ethylene terephthalate—See *glycol modified polyethylene terephthalate*.

polycyclohexylenedimethylene terephthalate—Thermoplastic polyester which can be prepared by polycondensation of cyclohexylenedimethylenediol and terephthalic acid. It is usually filled with glass fiber for high-heat applications. Processed by molding and extrusion. Also called PCT.

polydimethylsiloxane—Silicon-based organic polymer. Optically clear, inert and non-flammable. Can be manufactured in a range of viscosities, from a viscous liquid to a rubbery semi-solid. Uses include adhesives and sealants, lubricants, mold-release agents, cosmetics, and hair conditioners. Also called PDMS.

polyester—A large class of polymers usually made by polycondensation of polyol with polycarboxylic acid or anhydride, or polycondensation of hydroxycarboxylic acid. Polyesters are characterized by the presence of a repeating carbonyloxy group in the backbone and can be aliphatic or aromatic. There are thermosetting polyesters consisting of alkyd resins and unsaturated polymers, and thermoplastic polyesters including elastomers. The properties, processing techniques, and applications of polyesters vary widely. Also called copolyester.

polyester terephthalate—See *terephthalate polyester*.

polyester thermoplastic elastomer—These thermoplastic elastomers are mostly copolymers containing soft polyether and hard polyester blocks. They have a broad flexibility/stiffness spectrum, good dielectric strength, chemical resistance, exceptional dynamic performance, superior appearance, good creep resistance, and excellent retention of properties at temperatures ranging from –40°F (–40°C) to 300°F (149°C), but require protection from ultraviolet radiation. Processed by injection, blow, and rotational molding, extrusion casting, and film blowing. Uses include electrical insulation, medical products, exterior automotive parts, business equipment, and consumer goods. Also called copolyester thermoplastic rubber, copolyester TPE, polyester thermoplastic rubber, polyester TPE, TEEE.

polyester thermoplastic rubber—See *polyester thermoplastic elastomer*.

polyester TPE—See *polyester thermoplastic elastomer*.

polyestercarbonate—See *aromatic polyester estercarbonate*.

polyether polyimide—See *polyetherimide*.

polyether polysulfone—See *polyethersulfone*.

polyetheretherketone—A partially crystalline thermoplastic containing repeating ether and keto groups in the backbone. Its systematic name is poly(oxy-1,4-phenyleneoxy-1,4-phenylenecarbonyl-1,4-phenylene). PEEK has superb chemical resistance, toughness, rigidity, loadbearing properties, thermal stability, radiation resistance, and very low flammability. Processed readily by injection molding, spinning, cold forming, and extrusion. Used in fibers, films, automotive engine parts, aerospace composites, and wire and cable insulation. Also called PEEK.

polyetherimide—Thermoplastic containing repeating cyclic imide and ether groups in the backbone. They are prepared by cyclopolycondensation of diether dianhydrides such as that of benzoic acid and bisphenol A, and aromatic diamine. Polyetherimides have good chemical resistance, thermal and hydrolytic stability, and good dielectric properties and resistance to creep at elevated temperatures. Processed by extrusion, thermoforming, compression molding, injection molding, blow molding, and film techniques. Used in automotive parts, jet engine components, surgical instruments, industrial fluid and air handling components, food packaging, cookware, and computer disks. Also called PEI, polyether polyimide.

polyetherketone—Thermoplastic with excellent high-temperature properties and thermal stability. Used in advanced composites, wire coating, chemical-resistant filters, integrated circuit wafer carriers, and bearings. Synthesized by polyarolyation or polyetherization. Also called PEK.

polyetherketoneetherketoneketone—A partially crystalline engineering thermoplastic containing repeating ether and ketone groups in the backbone. PEKEKK has a higher melting point than PEEK. It has high strength, stiffness, chemical resistance and impact resistance over a wide range of temperatures, and low coefficient of friction and thermal expansion. Used for surgical implant, automotive, electrical/electronic applications and as a composite matrix. Also called PEKEKK.

polyetherketoneketone—A partially crystalline thermoplastic containing repeating ether and ketone groups in the backbone. PEKK has excellent chemical resistance, strength, and thermal and dimensional stability. It is used in the chemical processing, and oil and gas industries. Also called PEKK.

polyethersulfone—A thermoplastic containing repeating sulfone and ether groups in its wholy aromatic backbone. It has excellent thermal stability in air and water, good transparency, very low flammability and smoke emission, good dimensional stability, rigidity, and toughness. It has low mold shrinkage and is a good, heat resistant dielectric. Polyethersulfone has good resistance to acids and bases but is attacked by many organic solvents, has poor weatherability, and is subject to stress cracking. Processed by injection molding, extrusion, blow molding, and compression molding; but requires high processing temperatures. Used in high temperature electrical applications such as multipin connectors, bakery oven windows, medical devices, radomes, structural aircraft components, appliance housings, and auto parts. Also called PES, polyether polysulfone.

polyethylene—A family of polyolefins consisting of linear and branched polyethylenes. Polyethylenes are thermoplastics but can be crosslinked by irradiation or chemically, showing improved strength and dielectric properties. All linear polyethylenes, except the high density grade, are prepared by copolymerization of ethylene with higher olefins. Branched polyethylenes are prepared from ethylene alone or together with polar comonomers such as vinyl acetate. The density, melt index, crystallinity, degree of branching, molecular weight, polydispersity, and related properties of polyethylenes vary widely depending on the catalysts and methods of polymerization and on modifying comonomers and treatments. Polyethylenes have good impact resistance at low temperatures, good chemical resistance, and good moisture resistance, but high thermal expansion, poor weatherability, poor thermal stability and resistance to stress cracking. They are readily processable by all thermoplastic methods but are flammable and difficult to adhesively bond. Food grades are available. Processed by extrusion, blow and injection molding, thermoforming. Used very broadly as films, coatings, in containers and consumer goods, electrical insulation, and piping. Also called PE.

polyethylene-acrylic acid copolymer—Copolymer of ethylene with acrylic acid containing carboxyl groups distributed along the backbone and side chains of the molecule. A flexible thermoplastic with water and chemical resistance and barrier properties similar to those of low density polyethylene and enhanced adhesion, optics, toughness, and hot tack properties, compared to the latter. Contains 3–20% acrylic acid, with density and adhesion to polar substrates increasing with increasing acrylic acid content. FDA approved for direct contact with food. Processed by extrusion, blow and film methods and extrusion coating. Uses include pipe caps, hoses, gaskets, gloves, hospital sheeting, diaper liners, and packaging film. Also called EAA, ethylene-acrylic acid copolymer.

polyethylene copolymer—Thermoplastic prepared by copolymerization of ethylene with other olefins such as propylene. Processed by molding and extrusion.

polyethylene naphthalate—A polyester, chemically similar to PET but with better temperature resistance and better barrier properties. It is used for production of beverage bottles and sailcloth, and as films in the electrical and electronic industries. Also called PEN.

polyethylene terephthalate—A saturated polyester thermoplastic prepared by polycondensation of ethylene glycol with terephthalic acid or its dimethyl ester. PET is extremely hard, wear resistant, dimensionally stable, resistant to chemicals, and has good dielectric properties. Its tensile strength and thermal stability improve dramatically with increasing crystallinity and orientation. PET is processed by high temperature extrusion, injection and blow molding, melt spinning, and film extrusion. Uses include fiber, FDA approved film for food packaging, beverage bottles, magnetic tapes, photographic films, and food trays. Also called PET, PETE.

polyfluorocarbon—See *fluoropolymer*.

polyfluorohydrocarbon—See *fluoropolymer*.

polyformaldehyde—See *acetal resin*.

polyhexamethylene sebacamide—See *nylon 610*.

polyhexamethyleneadipamide—See *nylon 66*.

polyimide—Thermoset polyimides are usually supplied as polyamic acids and require curing at elevated temperatures. They have good processability due to their low melt viscosity. They are processed by transfer and injection molding, lamination, and coating. Thermoplastic polyimides have improved toughness compared to thermoset polyimides. They are also remoldable and reformable. Due to the relatively high glass transition temperature of thermoplastic polyimides and their high melt viscosities, high processing temperatures are required, which may exceed the material's decomposition temperature. Uses of both thermoset and thermoplastic polyimides include jet engine components, compressor parts, electronic coatings, automotive parts such as seal rings in transmissions, and business machine parts. Also called PI.

polyketone—A class of thermoplastics, the most important representatives of which are polyetherketone and polyetheretherketone. Characterized by the presence of repeating keto groups in the backbone. Also called ketone resin.

polylactic acid—A biodegradable, thermoplastic, aliphatic polyester derived from renewable resources, such as corn starch and sugarcane. It can be processed like most thermoplastics into fiber and film. It is used in a number of biomedical applications, such as sutures and stents; and, being biodegradable, is also used for packaging and disposable tableware. Also called PLA.

polymer—High molecular weight substance with molecules resembling linear, branched, crosslinked, or otherwise shaped chains consisting of repeating molecular groups. Synthetic polymers are prepared by polymerization of one or more monomers. The monomers comprise low-molecular-weight reactive substances, often containing >1 reactive molecular bond or chemical bond. Natural polymers have molecular structures similar to synthetic polymers, and have various degrees of purity. Also called resin, synthetic resin. See also *plastic*.

polymer coated material joining—This technology involves precoating non-thermoplastic components with a layer of thermoplastic. The components are then joined by welding the plastic coatings together using a plastics welding technique. The mechanical integrity of these joints relies on the bonding between the thermoplastic coating and the non-thermoplastic substrate, and on the strength of the weld between the coatings. Also called PCM.

polymethyl methacrylate—An acrylic resin that is made by polymerizing the monomer methyl methacrylate. Good optical clarity (92% light transmission), excellent resistance to weathering, good impact strength and electrical properties, non-toxic, tasteless. Powders can be injection molded, extruded, and compression molded. Liquid can be cast into rods, sheets, lenses. Used in airplane canopies, signs, lighting fixtures. Also called PMMA.

polymethylpentene—A thermoplastic polyolefin prepared by Ziegler copolymerization of 4-methyl-1-pentene. It has very low density ($0.83 g/cm^3$); high light transmission; high melting point; good rigidity, dielectric, and tensile properties and chemical resistance. Processed by injection molding, extrusion, and blow molding. Used in laboratory ware, extrusion-coated paper, high-intensity light fixtures, automotive parts such as radiator plugs, sight glasses, wire insulation, and small appliances. Also called PMP.

polyolefin—A large class of carbon-chain elastomeric and thermoplastic polymers usually prepared by addition (co)polymerization of olefins or alkenes such as ethylene. The most important representatives of this class are polyethylene and polypropylene. There are branched and linear polyolefins and some contain polar pendant groups or are halogenated. Unmodified polyolefins are characterized by relatively low thermal stability and a nonporous, nonpolar surface with poor adhesive properties. Processed by extrusion, injection molding, blow molding, and rotational molding. Other thermoplastic processes are used less frequently. This class of plastics is used more and has more applications than any other. Also called olefinic plastic, olefinic resin.

polyolefin thermoplastic rubber—See *olefinic thermoplastic elastomer*.

polyoxymethylene—See *acetal resin*.

polyperfluoroalkoxyethylene—See *perfluoroalkoxy resin*.

polyphenylene ether—See *polyphenylene oxide*.

polyphenylene oxide—Amorphous thermoplastics containing repeating ether groups in the backbone. They are prepared by oxidative polycondensation of substituted phenols such as 2,6-dimethylphenol and are characterized by a wide range of service temperatures and excellent dielectric properties and resistance to acids and bases. They have outstanding impact and fatigue strength and resistance to radiation and oxidation. They are miscible with polystyrene and other polymers in a wide range of ratios and are used usually in modified or alloyed form. Processed by extrusion and injection molding. Used in automotive parts, battery cases for aerospace use, and appliances. Also called polyarylene ether, polyarylene oxide, polyaryl ether, polyaryl oxide, polyphenylene ether, PPE, PPO. See also *modified polyphenylene oxide*.

polyphenylene oxide nylon alloy—Thermoplastic with excellent heat resistance, toughness, and chemical resistance and improved resistance to organic solvents, compared with modified PPO. Processed by molding and extrusion. Used in automotive body panels.

polyphenylene sulfide—A high-performance engineering thermoplastic. Its linear chains consist of benzene rings para-substituted with sulfur atom links. PPS has excellent thermal stability; good resistance to solvents and chemicals, except for chlorinated hydrocarbons; good radiation resistance; excellent dimensional stability; low water absorption; and good dielectric properties, but somewhat low impact strength. PPS is nonburning. Processing of PPS is hampered by its high melting point and is achieved at elevated temperatures by injection molding, compression molding, transfer molding, and extrusion. Used in hydraulic components, bearings, valves, electronic parts, small appliances such as hair dryers, and under-the-hood automotive parts. Also, PPS spheres are used as fillers in various plastics. Also called polythiophenylene, PPS.

polyphenylene sulfide sulfone—Thermoplastic with good thermal stability, chemical resistance, and dielectric properties and low flammability and creep. Processed by injection molding. Used in electrical components. Also called polyphenylenesulfidesulfone.

polyphenylenesulfidesulfone—See *polyphenylene sulfide sulfone*.

polyphenylsulfone—An amorphous high performance thermoplastic, offering better impact resistance and chemical resistance than polysulfone and polyetherimide. It also has superior hydrolysis resistance compared to other amorphous thermoplastics and can be steam sterilized, making it an excellent choice for medical devices, such as sterilization trays, and dental and surgical instrument handles. Also called PPSU.

polyphthalamide—Thermoplastic aromatic polyamide prepared by polymerization of aromatic diamine and phthalic acid or its derivatives (e.g., anhydride). These plastics are characterized by high heat resistance, good retention of mechanical and dielectric properties at elevated temperatures, good dielectric properties, chemical resistance, high stiffness, and low flammability. High crystallinity results in good mechanical properties such as impact strength. Resistance to light is somewhat low. Processing is difficult because of high melting point. Processed by solution casting, molding, and extrusion. Uses include film, fibers, and molded parts requiring good surface finish. Also called PPA.

polypropylene—A carbon chain thermoplastic comprised of propylene homopolymer prepared by stereospecific polymerization in the presence of Ziegler Natta catalysts. The majority of PP is isotactic. PP has low density and good flexibility and resistance to chemicals, abrasion, moisture, and stress cracking, but decreased dimensional stability, mechanical strength, and resistance to UV light and heat. PP is flammable. Processed by injection molding, spinning, extrusion, and film techniques. Used as films for pressure sensitive tapes, packaging, liners, and shrink films, and as fibers in textiles. Also called PP.

polypyrrole—A polymer of pyrrole, a five-membered heterocyclic substance with one nitrogen and four carbon atoms and with two double bonds. The polymer can be prepared via electrochemical polymerization. Polymers thus prepared are doped by electrolyte anion and are electrically conductive. Polypyrrole is used in lightweight secondary batteries, as electromagnetic interference shielding, anodic coatings, photoconductors, solar cells, and transistors.

polysiloxane—See *silicone*.

polystyrene—A thermoplastic produced by homopolymerization of styrene. It has good rigidity, high dimensional stability, low moisture absorption, optical clarity, high gloss, and good dielectric properties. On the other hand, it is flammable, has poor impact strength and resistance to solvents, heat, UV radiation, and chemicals. Processed by injection molding, extrusion, compression molding, and foam molding. Used widely in medical devices, household items such as cutlery handles and housewares, food packaging, electronics, and foam insulation. Also called polystyrol, PS. See also *expanded polystyrene, general purpose polystyrene, impact polystyrene*.

polystyrol—See *polystyrene*.

polysulfide—A large class of polymers containing repeating thio linkages in the aromatic, alicyclic, or aliphatic backbone. The most important families of polysulfides are polythiophenylenes and sulfide rubber. The former resemble polyethers with sulfur substituting oxygen, whereas the latter has usually a series of connected sulfur atoms in the repeating unit.

polysulfide adhesive—Flexible, one- or two-part adhesives that cure by a crosslinking reaction. Also called sulfide adhesive.

polysulfone—A class of thermoplastics characterized by the presence of sulfone linkages in their repeating units. Most polysulfones are aromatic and also contain ether linkages to enhance oxidation resistance. The most important of these are polyarylsulfone and polyethersulfone. As a class, polysulfones show excellent thermal stability, low creep, good dielectric properties, transparency, self-extinguishing properties, and resistance to chemicals, but are attacked by many solvents, have poor weatherability, are subject to stress cracking, and require high processing temperatures. Processed by injection molding, compression molding, blow molding, and extrusion. Used in appliances, electronics, automotive parts, and electric insulators. A high-performance engineering thermoplastic, called polysulfone in the trade, consists of diaryl sulfone groups linked by oxygen atoms and shares many properties typical for its class. It has good rigidity at elevated temperatures, good impact strength, and resists alkalies and acids but is attacked by polar solvents. Used for medical devices, in food processing equipment, electronics, chemical apparatus, and battery cells. Also called PSO, PSU.

polytetrafluoroethylene—Thermoplastic prepared by radical polymerization of tetrafluoroethylene. It has low dielectric constant, superior chemical resistance, very high thermal stability, low friction coefficient, excellent antiadhesive properties, low flammability, and high weatherability. Impact resistance of PTFE is high, but permeability is also high whereas strength and creep resistance are relatively low. The very high melt viscosity of PTFE restricts its processing to sinter molding and powder coating. Uses include coatings for cooking utensils, chemical apparatus, electrical and nonstick items, bearings, containers. Also, PTFE spheres are used as fillers and PTFE oil is used as a lubricant in various plastics. Also called PTFE, TFE.

polytetramethyleneadipamide—See *nylon 46*.

polytetramethylene terephthalate—See *polybutylene terephthalate*.

polythiophenylene—See *polyphenylene sulfide*.

polyurethane—A large class of polymers, the backbone of which consists of repeating units containing urethane group. PUs are usually prepared by interfacial polycondensation of polyisocyanates with polyols. The latter may be based on polyesters or polyethers or both. The most important members of this class are urethane rubbers, nonelastomeric thermoplastic PUs, urethane thermoplastic elastomers , and thermoset urethane resins. PUs may be rigid or soft and flexible, cellular or solid and offer a wide range of properties depending on composition and molecular structure. In general they have high abrasion resistance, good retention of properties at low temperatures, and good foamability, but poor heat resistance, weatherability, and resistance to solvents. PUs are flammable and are made with toxic substances (isocyanates). Nonelastomeric thermoplastic PUs are not chemically crosslinked and are processed by injection molding and extrusion. Thermoset PUs can be cured at moderate and ambient temperatures and give foams with good heat insulating properties. They are processed mainly by reaction injection molding, various foam techniques, casting, and coating. PUs are used in load bearing rollers and wheels, acoustic damping materials, sporting goods, seals and gaskets, rigid and flexible foams for heat insulation and other uses, potting, and encapsulation. Also called PU, urethane polymer. See also *nonelastomeric thermoplastic polyurethane, nonelastomeric thermosetting polyurethane, urethane thermoplastic elastomer*.

polyurethane adhesive—One- or two-part adhesives that cure by a polymerization reaction to form temperature resistant bonds that are both rigid and flexible.

polyurethane thermoplastic rubber—See *urethane thermoplastic elastomer*.

polyurethane TPE—See *urethane thermoplastic elastomer*.

polyvinyl chloride—A thermoplastic prepared by free-radical polymerization of vinyl chloride in dispersion (emulsion), bulk, or suspension processes. A small amount of comonomer is sometimes added to enhance adhesion or other properties. Unmodified PVC is rigid and requires plasticizers to make it more flexible. The main end forms of PVC are rigid and flexible. The flexible form is often made from plastisols, suspensions of PVC in liquid plasticizers. PVC can be chlorinated to increase its heat deflection temperature and tensile strength and to reduce flammability and smoke generation. PVC is dimensionally stable, largely nonflammable, and resistant to weathering, but has limited thermal stability, high density, and is attacked by many solvents. Processed by injection molding, calandering, extrusion, powder coating, blow molding, extrusion coating, and film techniques. Used very widely as films, fabric coatings, wire coatings, toys, bottles, and pipes. Also called PVC. See also *unplasticized polyvinyl chloride*.

polyvinyl dichloride—See *polyvinylidene chloride*.

polyvinyl fluoride—A highly crystalline material with high toughness, high flexibility, outstanding weathering resistance, and good abrasion resistance. Commercially available only as a film. Useful properties are maintained over a temperature range of –94°F (–70°C) to 230°F (110°C). Used for packaging, glazing, and electrical applications. Also called PVF.

polyvinylidene chloride—A stereoregular, thermoplastic polymer derived by the polymerization of vinylidene chloride or copolymerization of vinylidene chloride with lesser amounts of other unsaturated compounds. This polymer is resistant to abrasion and chemical attack, impermeable to flavor, and possesses low vapor transmission properties. Uses include packaging for food, insecticide-impregnated multiwall paper bags, pipes for chemical processing equipment, seat covers, upholstery, fibers, bristles, and latex coatings. Also called polyvinyl dichloride, PVDC.

polyvinylidene fluoride—Thermoplastic prepared from vinylidene fluoride. It has substantially higher strength, wear resistance, and creep resistance than other fluoropolymers but relatively high dielectric constant and loss factor. PVDF is nonflammable, resists most solvents, and has excellent weatherability. Its service temperature limit and chemical resistance are lower than those of perfluoropolymers. PVDF is processed readily by extrusion, injection molding, transfer molding, and powder or dispersion coating. Uses include electrical insulation, pipes, chemical apparatus, coatings, films, containers, and fibers. Also called PVDF.

polyxylyleneadipamide—See *nylon MXD6*.

POM—See *acetal resin*.

pot-life—See *working life*.

powdered carbon—See *carbon filler*.

powdered graphite—See *graphite filler*.

PP—See *polypropylene*.

PPA—See *polyphthalamide*.

PPE—See *polyphenylene oxide*.

pphm—See *parts per hundred million*.

ppm—See *parts per million*.

PPO—See *polyphenylene oxide*.

PPS—See *polyphenylene sulfide*.

PPSU—See *polyphenylsulfone*.

press fit—See *interference fit*.

pressure sensitive adhesive—An adhesive that requires applied pressure on the parts for bonding to occur. Usually composed of a rubbery elastomer and modifying tackifier, pressure sensitive adhesives are applied to the parts as solvent-based adhesives or hot melts; curing does not usually occur. They adhere tenaciously under slight pressure and are highly thixotropic. Disadvantages include limited temperature capability and susceptibility to oxidative degradation. See also *contact adhesive*.

primer—In adhesive bonding, a reactive chemical species dispersed in a solvent that is applied to the part surface by spraying or brushing. After the solvent is flashed off, the part surface may be bonded immediately, as in polyolefin primers for cyanoacrylates, or may require time to react with atmospheric moisture, as in silane and isocyanate-based primers used for silicone and polyurethane-based adhesives, respectively. Primers generally contain a multifunctional chemically reactive species capable of acting as a chemical bridge between the substrate and the adhesive. Primers are commonly used with acetals, fluoropolymers, polybutylene terephthalate, silicone, polyurethane, and polyolefins. Coatings applied on a substrate prior to subsequent coatings or topcoat in order to seal the pores, improve adhesion of the topcoat, improve corrosion protection, hide surface imperfections or color, etc. Usually based on polymers with functional additives. Applied by the same techniques as coatings. Also called adhesion promoter, primer coating.

primer coating—See *primer*.

processing agents—Agents or media used in the manufacture, preparation and treatment of a material or article to improve its processing or properties. The agents often become a part of the material.

processing defect—Structural and other defect in a material or article induced inadvertently during manufacturing, preparation and treatment processes by using wrong tooling, process parameters, ingredients, part design, etc. Usually preventable. Also called processing flaw.

processing flaw—See *processing defect*.

processing methods—Method names and designations for material or article manufacturing, preparation and treatment processes. Note: both common and standardized names are used.

processing parameters—Measurable parameters such as temperature prescribed or maintained during material or article manufacture, preparation and treatment processes.

processing time—Time required for the completion of a process in the manufacture, preparation and treatment of a material or article. Also called process time.

process time—See *processing time*.

projection—Raised profile on a surface; used to direct welding energy.

promoter—See *accelerator*.

propene—See *propylene*.

propylene—An alkene (unsaturated aliphatic hydrocarbon) with three carbon atoms, $CH_2=CHCH_3$. A colorless, highly flammable gas. Autoignition temperature 455°C (851°F). Derived by thermal cracking of ethylene or from naphtha. Used as monomer in polymer and organic synthesis. Also called propene.

PS—See *polystyrene*.

PSO—See *polysulfone*.

PSU—See *polysulfone*.

PTFE—See *polytetrafluoroethylene*.

PU—See *polyurethane*.

PU TPE—See *urethane thermoplastic elastomer*.

pullout strength—The resistance of a screw or insert to forces that tend to pull it out of the part or boss.

pulp—See *cellulose*.

PUR—See *nonelastomeric thermosetting polyurethane*.

PUR TPE—See *urethane thermoplastic elastomer*.

PVC—See *polyvinyl chloride*.

PVC-C—See *chlorinated polyvinyl chloride*.

PVC-U—See *unplasticized polyvinyl chloride*.

PVDC—See *polyvinylidene chloride*.

PVDF—See *polyvinylidene fluoride*.

PVF—See *polyvinyl fluoride*.

R

radiation—Electromagnetic emission of energy from the surface of an object due to the object's temperature; the frequency of the electromagnetic energy increases as the temperature increases. See also *conduction, convection*.

radiation dosage—See *radiation dose*.

radiation dose—Amount of ionizing radiation energy received or absorbed by a material during exposure. Also called ionizing radiation dose, radiation dosage.

radiation resistant materials—Materials that resist degradation on long- and medium-term or repeated exposure to ionizing radiation. Radiation damage to materials includes swelling, radiolysis, blistering, changes in electrical and mechanical properties, etc. There are different mechanisms of radiation damage but most can be linked to free-radical reactions. The resistance of materials to radiation can be improved by stabilizing them with agents that can neutralize free radicals, such as dimethyl sulfoxide, carbohydrates and various reducing agents. Also called radiation stabilized material.

radiation stabilized material—See *radiation resistant materials*.

radio frequency welding—A method of welding thermoplastics that uses a radio frequency electromagnetic field (usually 27.1 MHz) to apply the necessary heat. The radio frequency field is usually applied with a metal die in the shape of the joint, causing an increase in molecular motion in the region of the joint and an increase in temperature that generates heat in the parts being joined. The parts melt in the joint region, allowing molecular diffusion across the joint interface and weld formation after cooling. Commonly used for sealing polar plastic sheets and films. Also called dielectric welding, HF welding, high frequency welding, RF welding.

reaction injection molding system—Liquid composition based on thermoset resins, prepolymers, monomers, or mixtures thereof. The components of the systems are mixed together at a given ratio and then poured into a mold under pressure wherein they polymerize and cure at elevated temperatures to form a molded part. The majority of RIM systems are based on polyurethanes or polyurethane-polyurea hybrids. They are used to produce solid or integral skin flexible foam moldings. The solid moldings are elastomeric with a high or low modulus. The low modulus moldings are used as automobile fascia, bumper covers, and trim. The high modulus moldings are used in large industrial and consumer parts. Either can be reinforced with fillers to improve the flexural modulus, thermal properties, and dimensional stability. The foam moldings are used as steering wheels, armrests, and protective automotive covers. Other RIM systems are based on polyureas, polyisocyanurates, nylons, acrylamate resins, or polydicyclopentadiene. Also called LIM, LIM system, liquid injection molding system, RIM, RIM system.

regrind—In polymer processing, refers to material that has been recycled; a proportion may be added to some polymers to reduce cost.

relative humidity—The ratio of the actual vapor pressure of the air to the saturation vapor pressure. Also called RH.

relative viscosity—The ratio of solution viscosity to the viscosity of the solvent. Also called RV, viscosity ratio.

replaceable tip—In ultrasonic welding, a machined titanium forming tool threaded to attach to a horn. Commonly used in ultrasonic staking and spot welding.

resin—See *polymer*.

resistance to tear propagation—See *tear propagation resistance*.

resistive implant welding—A method for joining plastics and composites in which heat is generated by application of an electric current to a conductive heating element placed at the joint interface. Thermoplastic material at the joint interface melts and fuses, forming a weld. Thermosets require a thermoplastic interlayer for bonding. The conductive heating element is usually stainless steel or carbon fiber prepeg and remains in the joint after welding.

resorcinol modified phenolic resin—A phenolic resin which has been modified by the addition of resorcinol. This thermosetting resin is commonly used in applications that require good heat resistance, dimensional stability, and creep resistance. Also called resorcinol phenolic resin.

resorcinol phenolic resin—See *resorcinol modified phenolic resin*.

retarder—In solvent welding, a slowly drying solvent used to reduce the evaporation rate of a rapidly drying solvent to prevent the formation of condensate on the bond surface.

RF welding—See *radio frequency welding*.

RH—See *relative humidity*.

ribs—Additions to a component wall to improve strength and stiffness.

rigid PVC—See *unplasticized polyvinyl chloride*.

rigid thermoplastic polyurethane—See *nonelastomeric thermoplastic polyurethane*.

rigid thermoplastic urethane—See *nonelastomeric thermoplastic polyurethane*.

RIM—See *reaction injection molding system*.

RIM system—See *reaction injection molding system*.

riveting—An assembly process in which a short rod with a head on one side is inserted into a preformed hole in two or more parts. The straight end is then pressed or hammered in order to form another head.

Rockwell hardness—A number derived from the net increase in the depth of impression as the load on an indenter is increased from a fixed minor load (10 kgf; 22 lbf) to a major load and then returned to the minor load. This number consists of the number of scale divisions (each corresponding to 0.002 mm (0.00008 inches) vertical movement of the indentor) and scale symbol. Rockwell scales, designated by a single capital letter of English alphabet, vary depending on the diameter of the indentor and the major load. For example, scale A indicates the use of a diamond indentor and major load 60 kgf (132 lbf), E—1/8" (3.25 mm) ball indentor and 100 kgf (220 lbf), K—same ball and 150 kgf (330 lbf), M—1/4" (6.35 mm) ball and 100 kgf (220 lbf), R—1/2" (12.7 mm) ball and 60 kgf (132 lbf). The hardness increases in the order of R, M, K, E, and A scales.

room temperature vulcanizing silicone—Silicone that is vulcanized or cured at room temperature by a chemical reaction. Room temperature vulcanizing is commonly used for silicones and other thermoset elastomers. Also called RTV silicone.

rotational welding—See *spin welding*.

rotation speed—Rate of angular motion.

RTPU—See *nonelastomeric thermoplastic polyurethane*.

RTV silicone—See *room temperature vulcanizing silicone*.

rubber—See *thermosetting elastomer*.

run-up time—In inertia spin welding, the period of time allowed for the welding tool to reach operating speed.

RV—See *relative viscosity*.

S

SAN—See *styrene-acrylonitrile copolymer*.

satinizing—In adhesive bonding and solvent welding, a chemical etching process in which a mildly acidic solution is used to produce uniform anchor points on a part surface. Finishes, cements, or adhesives then bond to the anchor points, resulting in strong adhesion. Developed by DuPont for Delrin acetal.

SAZ—See *solvent affected zone*.

seal initiation temperature—The lower limit of a heat-seal temperature range at which a thermoplastic material such as film is beginning to fuse and adhere to itself or another thermoplastic material.

seating torque—A level of torque below the stripping torque at which clamp force is optimized. Seating torque is generally 50–75% of the stripping torque. High seating torques are preferred. See also *stripping torque*.

secant modulus—The slope of a line drawn from the origin to a point on the stress-strain curve for a material that corresponds to a particular strain. Used in designing parts subjected to short-term, infrequent, intermittent stress for plastics in which the stress-strain curve is nonlinear.

self-centering—Property of joint design which allows the parts to be automatically positioned as the welding proceeds.

self-reinforcing plastics—Plastics with densely packed, fibrous polymer chains. Liquid crystal polymers are called self-reinforcing plastics.

self-tapping screw—A method of mechanically fastening two plastic parts together in which screws inserted into a pilot hole form mating threads in the plastic part. Self-tapping screws can be either thread-forming or thread-cutting. See also *thread-cutting screw, thread-forming screw*.

shear joint—A joint design used in welding in which the thermoplastic parts melt in a telescoping action due to a small interference between the mating parts.

shelf life—Time during which a material retains its storage stability under specified conditions. Also called storage life.

Shore hardness—Indentation hardness of a material as determined by the depth of an indentation made with an indentor of the Shore-type durometer. The scale reading on this durometer is from 0, corresponding to 2.5 mm (0.1 inches) depth, to 100 for zero depth. The Shore A indenter has a sharp point, is spring-loaded to 0.822 kgf (1.81 lbf), and is used for softer plastics. The Shore B indenter has a blunt point, is spring-loaded to 10 lbf (4.5 kgf), and is used for harder plastics.

short glass fiber—See *chopped glass fiber*.

shrink mark—See *sink mark*.

SI—See *silicone*.

silicone—A polymer, the backbone of which consists of alternating silicon and oxygen atoms. Pendant organic groups are attached to silicon atoms. They are usually made by hydrolyzing chlorosilanes, followed by polycondensation and crosslinking. Depending on the degree of crosslinking and the nature of pendant groups, silicones can be liquid, elastomeric, or rigid. Liquid silicones or silicone fluids such as dimethylsiloxane have very good antiadhesive properties, lubricity, resistance to heat and chemicals and are used as release agents, surfactants, and lubricants in plastics. As lubricants they improve wear resistance of plastics. Silicone elastomers, or rubbers, have high adhesion, resistance to compression set, flexibility, good dielectric properties, weatherability, low flammability, good moisture barrier properties, and thermal stability, but somewhat low strength. Optically clear grades are available. Processed by coating and injection molding. Used as optical fiber coatings, electronic connector encapsulants, printed circuit board coatings, seals, diaphragms, fabric coatings, medical products, adhesives, sealants, and glazing compounds. Rigid silicone resins offer good flexibility, weatherability, dirt release properties, dimensional stability, and are stronger and harder than silicone rubbers. The resins are attacked by halogenated solvents. Processed by coating, casting, injection molding, compression molding, and transfer molding. Used as coatings, adhesives, sealants, bonding agents, and molded parts. Also called polysiloxane, SI, silicone plastic, silicone rubber, siloxane.

silicone plastic—See *silicone*.

silicone rubber—See *silicone*.

siloxane—See *silicone*.

sink mark—A shallow depression on the surface of an injection molded part. Usually caused by collapse of the part surface following local internal shrinkage after the gate seals. Frequently occurs on the part face opposite to a face in which the section thickness increases, as in a rib. Also called shrink mark.

sliding velocity—The relative speed of movement of one body against the surface of another body (counterbody) without the loss of contact as in a sliding motion during wear and friction testing of materials. In the sliding motion, the velocity vectors of the body and the counterbody remain parallel and should be unequal if they have the same direction.

SMA—See *styrene-maleic anhydride copolymer*.

snap-fit—A method of mechanical fastening in which two plastic parts are joined by an interlocking configuration that is molded directly into the parts. A protrusion molded into one part, such as a hook or bead, is briefly deflected during assembly and engages a depression or undercut molded into the other part. The joint is usually stress-free after joining. Design is important in proper functioning of a snap-fit. Cantilever are the most common; other types include annular and torsional.

snap-on connection—A type of snap-fit connection in which one part is snapped onto another part, such as a lid on a container. Usually used with rounded parts.

soak method—See *dip method*.

sodium treatment—In adhesive bonding, a surface preparation technique in which the substrate is immersed in an aggressive etching solution containing either a sodium-napthalene complex dissolved in tetrahydrofuran or a sodium-ammonia complex dissolved in ammonia. This process increases surface roughness and the potential for mechanical interlocking by dissolving the amorphous regions of the part surface and increases surface reactivity and wettability by introducing carbonyl and carboxyl functional groups and unsaturated bonds. Sodium treatment darkens the part surface to a depth of 1nm and can substantially degrade the surface after extended exposure. Commonly used for fluorocarbons.

solubility—The maximum concentration of a compound in a binary mixture at a given temperature forming a homogeneous solution. Also called dissolving capacity.

solubility coefficient—The volume of a gas that can be dissolved by a unit volume of solvent at a fixed pressure and temperature.

solubility parameter—The capacity of a substance to be dissolved in another substance (e.g., of a polymer in a solvent). It represents the cohesive energy of molecules in a substance and determines the magnitude and the sign of the heat of mixing two substances in given concentrations. The magnitude and the sign of the heat of mixing determine the sign of the free energy of mixing. The solution occurs when the sign of the free energy of mixing is negative.

solvent affected zone—In solvent welding, the depth either side of the joint that the solvent diffuses into the thermoplastic. Also called SAZ.

solvent bonding—See *solvent welding*.

solvent welding—A method of joining two thermoplastics by application of a solvent to soften the part surfaces. Softening the polymer increases the movement of polymer chains, allowing them to intermingle at the joint interface. Adhesion occurs after solvent evaporation. Solvent application must be carefully controlled for optimal joint strength and to avoid damage to the part. Also called solvent bonding and solvent fusion.

solvent fusion—See *solvent welding*.

sonotrode—See *horn*.

spherulite—In plastics, a rounded aggregate of radiating lamellar crystals with amophous material between the crystals. Has the appearance of a pom-pom. Spherulites exist in most crystalline plastics and usually impinge on one another to form polyhedrons. They range in size from a few tenths of a micron in diameter to several millimeters.

spin welding—A method used for joining cylindrical thermoplastic parts. Frictional heat develops as one part spins against the other, stationary part, resulting in melting at the joint interface. Spinning is then stopped, and the parts are held together under pressure until cool. Also called friction welding, rotational welding.

stability—Resistance to degradation or deterioration from any of a number of conditions (heat, moisture, exposure to chemicals, prolonged storage, etc.). Also called durability.

staking—In part assembly, a process in which a thermoplastic stud protruding out of the parts being joined is made to soften and flow, forming a head that locks the parts together. Flow can occur as a result of heat or pressure. An alternate form of staking occurs when a thermoplastic is forced to cold flow around a metal insert placed into a plastic boss, locking the insert in place.

static coefficient of friction—The ratio of the force that is required to start the friction motion of one surface against another to the force, usually gravitational, acting perpendicular to the two surfaces in contact.

steady state—In spin and vibration welding, the period in the welding cycle where relative part displacement against time is constant.

steric hindrance—A spatial arrangement of the atoms of a molecule that blocks a reaction of the molecule with another molecule.

stibic anhydride—See *antimony pentoxide*.

storage life—See *shelf life*.

strain—The per unit change, due to force, in the size or shape of a body referred to its original size or shape. Note: strain is nondimensional but is often expressed in unit of length per unit of length or percent. Also called mechanical strain.

stress concentration—Region of a part in which a sharp corner or small radius can lead to local generation of high stresses under certain loading conditions.

stress cracking—Appearance of external and/or internal cracks in a material as a result of stress that is lower than its short-term strength.

stress decrease—See *stress relaxation*.

stress relaxation—Time-dependent decrease in stress in a solid material as a result of changes in internal or external conditions. Also called stress decrease.

strip-to-drive ratio—The ratio of stripping torque to driving torque of a self-tapping screw. A high strip-to-drive ratio provides easier assembly and a higher safety factor.

stripping torque—The torque at which threads are stripped out of the molded part. High stripping torques are optimal. See also *seating torque*.

stud—See *boss*.

styrene—($C_6H_5CH{:}CH_2$) A colorless, oily liquid with a strong odor. Boils at 145.2°C (293.4°F); freezes at –30.63°C (–23.13°F). Soluble in alcohol and ether; insoluble in water. Polymerizes rapidly when exposed to heat, light, or a peroxide catalyst; polymerization may become explosive. Toxic by ingestion and inhalation; its TLV is 50ppm in air. Moderate fire risk; autoignition temperature is 490°C (914°F); explosive limit in air is 1.1– 6.1%. Derived from reaction of ethylene and benzene in the presence of aluminum chloride to form ethylbenzene, followed by catalytic dehydrogenation at 630°C (1166°F). Used in the production of polystyrene, styrene-butadiene rubber (SBR), acrylonitrile-butadiene-styrene (ABS), and styrene-acrylonitrile (SAN) resins; copolymers, rubber-modified polystyrene, styrenated polyesters, and protective coatings. Also called phenylethylene, vinylbenzene.

styrene-acrylonitrile copolymer—Thermoplastic copolymers of about 70% styrene and 30% acrylonitrile with higher strength, rigidity, and chemical resistance than polystyrene. Characterized by transparency, high heat deflection properties, excellent gloss, hardness, and dimensional stability. Have low continuous service temperature (185°F; 85°C) and impact strength. Processing is accomplished by injection molding, extrusion, injection-blow molding, and compression molding. Used in appliances (refrigerator shelves), housewares, instrument lenses for automobiles, medical devices, and electronics (cassette parts). Also called SAN.

styrene-butadiene block copolymer—This thermoplastic block polymer is amorphous and is composed of alternating block structures of butadiene and styrene. The butadiene blocks impart toughness and impact resistance to the plastic. The styrene blocks provide thermoplasticity, rigidity, high gloss, and compatibility with other styrenic resins. These polymers exhibit low gel content, water absorption, and mold shrinkage, as well as ease of processing. They may be used in food and drink containers, display containers, toy parts, blister packs, and shrink wrap. Also called butadiene-styrene block copolymer.

styrene-butadiene copolymer—A family of thermoplastic copolymers that are comprised of over 50% styrene. They are transparent, have high toughness, are easily processed, and have a low cost. They can be processed by sheet extrusion, injection molding, thermoforming, and blow molding, typically at temperatures between 380°F (193°C) and 450°F (232°C). When blended with general purpose polystyrene, applications include disposable packaging, blister packs, and other display packaging. Molded applications include medical devices, parts for toys, display boxes and racks, and office articles. Film applications include wraps.

styrene-butadiene-methyl methacrylate polymer—See *methyl methacrylate-butadiene-styrene terpolymer*.

styrene-maleic anhydride copolymer—Thermoplastic prepared by copolymerization of styrene with maleic anhydride. Using butadiene as a third monomer or alloying with ABS results in impact versions. They have high thermal stability and good adhesion, but limited chemical resistance and resistance to UV light. Impact versions have good impact strength. Processed by injection molding, extrusion, and foam molding. Used in automotive parts such as consoles, small appliances, door panels, pump components, and business machines. Also called SMA.

styrene-maleic anhydride copolymer PBT alloy—Thermoplastic alloys of styrene-maleic anhydride copolymer with polybutylene terephthalate with improved dimensional stability and tensile strength. Processed by injection molding.

styrene-maleic anhydride copolymer polycarbonate alloy—Thermoplastic alloys of SMA with polycarbonate. Processed by injection molding and extrusion.

styrene-methyl methacrylate-butadiene polymer—-See *methyl methacrylate-butadiene-styrene terpolymer*.

styrene plastic—See *styrenics*.

styrene resin—See *styrenics*.

styrene rubber plastic—See *impact polystyrene*.

styrenic methyl methacrylate copolymer—A polymer of styrene and methyl methacrylate.

styrenic plastic—See *styrenics*.

styrenic resin—See *styrenics*.

styrenics—A class of thermoplastics prepared mainly by free- radical homopolymerization of styrene or copolymerization of styrene with other unsaturated monomers. The most important families of this class are ABS plastics, polystyrene, styrene-maleic anhydride copolymer, and styrene-acrylonitrile copolymers. The properties of styrenics vary widely with molecular structure, some attaining the high performance level of engineering plastics. Processed by blow and injection molding, extrusion, thermoforming, film techniques, and structural foam molding. Used very heavily in automotive parts, household goods, packaging, films, tools, containers, and pipes. Also called styrene plastic, styrene resin, styrenic plastic, styrenic resin.

styrenic thermoplastic elastomer—These thermoplastic elastomers are comprised of linear or branched copolymers containing polystyrene end blocks and elastomer (e.g., isoprene rubber) middle blocks. The elastomers have hardnesses ranging from 28 to 95 Shore A, tensile strengths from 300 to 5000 psi (2–35 MPa), and elongation from 250 to 1300%. They also retain their flexibility to temperatures as low as –112°F (–80°C) and have good dielectric properties and hydrolytic stability. They are processable by injection and blow molding and extrusion. Uses include adhesives, coatings, sealants, impact and asphalt modifiers, soles, medical devices, tubing, cable insulation, and automotive parts. Also called styrenic thermoplastic rubber, styrenic TPE, thermoplastic styrenic rubber.

styrenic thermoplastic rubber—See *styrenic thermoplastic elastomer*.

styrenic TPE—See *styrenic thermoplastic elastomer*.

sulfide adhesive—See *polysulfide adhesive*.

surface energy—See *surface tension*.

surface grafting—In adhesive bonding, a surface preparation technique in which a chemical species, such as vinyl acetate monomer, is grafted onto the substrate surface. Commonly used to graft vinylic compounds onto polyolefins.

surface roughening—In adhesive bonding, a commonly used surface preparation technique in which the substrate surface is mechanically abraded. The roughened surface increases bondability by dramatically increasing the number of sites available for mechanical interlocking.

surface roughness—The closely spaced unevenness of a solid surface (pits and projections); can be quantified by various methods (e.g., by using a profilometer in coatings).

surface tack—Stickiness of a surface of a material such as wet paint when touched.

surface tension—The cohesive force at a liquid surface measured as a force per unit length along the surface or the work which must be done to extend the area of a surface by a unit area (e.g., by a square centimeter). Also called free surface energy, surface energy.

surface velocity—Relative rate of motion between two surfaces.

sym-dichloroethylene—See *dichloroethylene 1,2*.

syndiotactic—A polymer molecule in which pendant groups and atoms attached to the main chain are arranged in a symmetrical and recurring fashion relative to it in a single plane.

synergistic effect—The boosting effect of one substance on the property of another so that the total effect of both substances in a mixture is greater that the sum of the effects of each substance individually, such as synergistic effect of zinc bis(dibutyldithiocarbamate) on the UV absorption by zinc oxide.

synthetic resin—See *polymer*.

synthetic rubber—See *thermosetting elastomer*.

T

Taber abrasion resistance—The weight loss of a plastic or other material specimen after it has been subjected to abrasion in a Taber abraser for a prescribed number of specimen disk rotations, usually 1000. A Taber abraser consists of an idling abrasive wheel, designated depending on the type and grit of the abrasive used as CS-10F, H 22, etc., and a rotary disk with the specimen mounted on it. The load is applied to the wheel. The produced motion simulates that of rolling with slip.

tack—See *tackiness*.

tackiness—Pull-resistance exerted by a material adhering completely to two separating surfaces; slight stickiness of the surface of a coating, apparent when it is pressed with the finger, a characteristic of cure. Also called tack.

tan delta—See *dielectric dissipation factor*.

tapping—The process of forming threads in the walls of a circular pilot hole in a plastic, metal, or similar material. See also *self-tapping screws*.

tear propagation force—See *tear propagation resistance*.

tear propagation resistance—The force required to propagate a slit in a flexible plastic film or thin sheeting at a constant rate of loading, calculated as an average between the initial and the maximum tear-propagation forces. Also called tear propagation force, resistance to tear propagation.

tearing energy—A function of strain energy density and crack length, often expressed in kN/m. Plots of tearing energy vs. fatigue crack growth rate are used to characterize the kinetics of fatigue crack extension in rubbers, which do not obey the classical theory of elasticity. Also called tearing energy parameter.

tearing energy parameter—See *tearing energy*.

TEEE—See *polyester thermoplastic elastomer*.

tensile elongation—See *elongation*.

tensile heat distortion temperature—See *heat deflection temperature*.

tensile properties—Properties describing the reaction of physical systems to tensile stress and strain.

tensile strength—The maximum tensile stress that a specimen can sustain in a test carried to failure. Note: the maximum stress can be measured at or after the failure or reached before the fracture, depending on the viscoelastic behavior of the material. Also called ultimate tensile strength, tensile strength at break.

tensile strength at break—See *tensile strength*.

tensile stress—The force related to the smallest original cross-section of the specimen at any time during a tensile test.

TEO—See *olefinic thermoplastic elastomer*.

terephthalate polyester—A thermoset unsaturated polyester based on terephthalic anhydride. Also called terephthalic polyester, polyester terephthalate.

terephthalic polyester—See *terephthalate polyester*.

tetrachloroethylene—A colorless, chemically stable and nonflammable liquid with ether odor, $CCl_2{=}CCl_2$. Irritant to skin. Derived by chlorination of hydrocarbons. Used as dry-cleaning solvent and drying agent for electronics.

tetrachloromethane—See *carbon tetrachloride*.

tetrafluoroethylene propylene copolymer—Thermosetting elastomeric polymer of tetrafluoroethylene and propylene having good chemical and heat resistance and flexibility. Used in auto parts.

TFE—See *polytetrafluoroethylene*.

thermal expansion coefficient—The change in volume per unit volume resulting from a change in temperature of the material. The mean coefficient of thermal expansion is commonly referenced to room temperature.

thermal properties—Properties related to the effects of heat on materials and heat transport. The effects of heat include the effects on structure, geometry, performance, aging, stress-strain behavior, etc.

thermal stability—The resistance of a material to decomposition, deterioration of properties or any type of degradation in storage under specified conditions. Also called oven stability, heat stability.

thermal treatment—In adhesive bonding, a surface preparation technique in which the substrate surface is oxidized by exposure to a blast of hot air (~500°C; 930°F). Oxidation proceeds by a free radical mechanism and introduces carbonyl, carboxyl, amide, and some hydroperoxide functional groups to the part surface, accompanied by chain scission and some crosslinking. Commonly used for polyolefins, thermal treatment increases wettability and interfacial diffusivity.

thermoforming—The process of heating a thermoplastic sheet to a point at which it softens, then applying differential pressure to make the sheet conform to the shape of a mold or die.

thermoplastic—Resin or plastic compounds which, after final processing, are capable of being repeatedly softened by heating and hardened by cooling by means of physical changes. There are a large number of thermoplastic polymers belonging to various classes such as polyolefins and polyamides. Also called thermoplastic polymer, thermoplastic resin.

thermoplastic elastomer—Polymers and blends that resemble vulcanized rubbers in that they can be deformed significantly at room temperature and return to their original shape after the stress has been removed, but are true thermoplastics that undergo normal plastic flow when heated in uncured state. The thermoplastic elastomers usually consist of hard and soft domains and can be of many chemical types (e.g., olefinic, urethane, polyester, polyamide, and styrenic). The properties of thermoplastic elastomers vary widely but all exhibit good impact strength and toughness. They are processed mainly by (co)extrusion and (co)molding. Uses include automotive parts, wire and cable insulators, adhesives, footware, and mechanical goods. Also called thermoplastic rubber, TPE, TPEL, TPV.

thermoplastic olefinic rubber—See *olefinic thermoplastic elastomer*.

thermoplastic polyamide rubber—See *polyamide thermoplastic elastomer*.

thermoplastic polymer—See *thermoplastic*.

thermoplastic polyolefin rubber—See *olefinic thermoplastic elastomer*.

thermoplastic polyurethane—A class of polyurethanes including rigid and elastomeric polymers that can be repeatedly made soft and pliable on heating and hard (flexible or rigid) on subsequent cooling. Also called TPU, TPUR. See also *nonelastomeric thermoplastic polyurethane*.

thermoplastic resin—See *thermoplastic*.

thermoplastic rubber—See *thermoplastic elastomer*.

thermoplastic styrenic rubber—See *styrenic thermoplastic elastomer*.

thermoset—Resin and plastic compounds which, after final processing, are substantially infusible and insoluble. Thermosets are often liquids at some stage in their manufacture or processing and are cured by heat, oxidation, radiation, or other means often in the presence of curing agents and catalysts. Curing proceeds via polymerization and/or cross-linking. Cured thermosets cannot be resoftened by heat. There are a large number of thermosetting polymers belonging to various classes such as alkyd and phenolic resins. Also called thermoset resin, thermosetting polymer, thermosetting resin.

thermoset resin—See *thermoset*.

thermosetting elastomer—A large class of polymers that can be stretched at room temperature to at least twice their original length and, after having been stretched and the stress removed, return with force to approximately their original length in a short time. To attain this elastic property the rubbers must be crosslinked or vulcanized, usually by heating in the presence of various crosslinking agents and catalysts. There are natural and synthetic rubbers. The most important synthetic rubber families are olefinic rubbers, dienic rubbers (nitrile, butadiene, neoprene), silicone rubbers, and urethane rubbers. Used often as impact modifiers/fillers in plastics. Also called synthetic rubber, rubber.

thermosetting polymer—See *thermoset*.

thermosetting resin—See *thermoset*.

thermotropic—A material in which the shape and packing of the macromolecules is affected by temperature.

thixotropy—The flow behaviour of an adhesive that causes the viscosity to reduce when stirred, mixed or dispensed but will then thicken on standing.

thread-cutting screw—A type of self-tapping screw that has a sharp cutting edge. Thread-cutting screws remove plastic chips as the screw is inserted, so that internal stresses produced are low. Only minimum reassemblies are possible. See also *self-tapping screw*.

thread-forming screw—A type of self-tapping screw that forms threads by displacing and deforming plastic material, which then flows around the screw head. No material is removed, and large internal stresses are produced in the plastic. See also *self-tapping screw*.

threaded mechanical insert—A metal, self-threading insert with an exterior locking feature for anchorage in the part to be joined. The threaded interior of the insert allows for repeated assembly and disassembly. Threaded mechanical inserts provide high strength joining of plastic parts with low stress.

through transmission infrared welding—An infrared welding method in which infrared radiation is transmitted through a part composed of a polymer that does not absorb infrared energy to the other part, composed of a polymer that does absorb infrared energy, at the weld interface. Heat builds up in the absorbing polymer and is transferred to the nonabsorbing polymer through conduction, causing melting at the weld interface. Parts flow together to form a weld. Also called TTIR. See also *infrared welding*.

Ti—See *titanium*.

tightening torque—The torque to which self-tapping screws are tightened. Tightening torque is greater than driving torque but less than stripping torque.

titanium—High strength, stiffness, good toughness, low density, good corrosion resistance, nonmagnetic, good heat-transfer and acoustic properties. Used in manufacturing horns and boosters for ultrasonic welding of plastics. Also called Ti.

toluene—($C_6H_5CH_3$) A colorless liquid with an aromatic odor. Boils at 110.7°C (231.3°F); freezes at –94.5°C (–138.1°F). Soluble in alcohol, benzene, and ether; insoluble in water. Flammable, fire risk; explosive limit in air is 1.27–7%; autoignition temperature is 536°C (997°F). Toxic by ingestion, inhalation, and skin absorption; TLV is 100 ppm in air. Derived from coal tar or the catalytic reforming of petroleum. Used in high-octane gasolines, explosives (TNT); as a solvent for paints, coatings, gums, resins, oils, rubber, and vinylorganosols; as a chemical intermediate in the production of polyurethanes and polyesters; in saccharin, medicines, dyes, perfumes, detergents, scintillation counters. Also called methylbenzene, phenylmethane, toluol.

toluol—See *toluene*.

tooling nest—See *fixture*.

torque—Angular force.

toughness—Property of a material indicating its ability to absorb energy by plastic deformation rather than crack or fracture.

TPE—See *thermoplastic elastomer*.

TPEL—See *thermoplastic elastomer*.

TPO—See *olefinic thermoplastic elastomer*.

TPU—See *thermoplastic polyurethane, urethane thermoplastic elastomer*.

TPUR—See *thermoplastic polyurethanes, nonelastomeric thermoplastic polyurethane*.

TPV—See *thermoplastic elastomer*.

transcrystalline growth—In adhesive bonding, a surface preparation technique in which adherends are molded against a high energy metallic substrate that induces the formation of crystallites at the surface of the plastic resulting in rod-like or columnar spherulites that form inward from the plastic-metal interface; these are thought to strengthen the surface by driving low molecular weight material into the interior. Surface oxidation may also occur, increasing surface reactivity and wettability. The effectiveness of transcrystalline growth is dependent on molding conditions, such as the cooling rate and mold surface. Commonly used for polyolefins, polyamides, and polyurethanes.

transducer—A piezoelectric device that converts high frequency electrical energy into high frequency mechanical vibrations. Also called converter. See also piezoelectric material.

trichloroethane -1,1,2—($CHCl_2CH_2Cl$) A clear, colorless liquid with a sweet odor. Soluble in ethers, alcohols, esters and ketones; insoluble in water. Nonflammable, boils at 113.7°C (236.7°F). Its TLV is 10 ppm in air; it is absorbed by skin. Used in organic synthesis and as a solvent for resins, waxes, oils, fats, and other products. Also called vinyl trichloride.

trichloroethylene—($CHCl{:}CCl_2$) A colorless, photoreactive liquid with a slight odor of chloroform. Soluble in common organic solvents; slightly soluble in water. Boils at 86.7°C (188.1°F); not flammable. Does not attack metals, even in the presence of moisture. TLV is 50 ppm in air; toxic by inhalation. Use in cosmetics, drugs, foods is prohibited; use as a solvent is prohibited in some states. Derived from reaction of tetrachloroethane with lime or alkali in the presence of water or from tetrachloroethane thermal decomposition followed by steam distillation. Used in metal degreasing, dry cleaning, diluent in paints and adhesives, cleaning and drying electronic parts, textile processing. Many other uses.

trigger force—In ultrasonic welding, the force applied to the parts being joined before ultrasonic vibrations are initiated. Produced by contact of the horn with the parts to be welded. Ultrasonic vibrations are begun after a particular trigger force or distance has been reached by the horn.

trigger point—In ultrasonic welding, the point in time during the welding operation when the horn is correctly positioned for the welding process, and ultrasonic vibrations are initiated. Ultrasonic triggering under applied clamp force assures reproducible welds. Reproducible welding cannot be achieved when ultrasonic vibrations are “pre-triggered”, and positive controlled clamping cannot be achieved when the horn touches the part while ultrasonically active.

TTIR—See *through transmission infrared welding*.

two-part adhesive—An adhesive in which the monomer and catalyst or hardener are separate from each other. The two reactive components separately have an indefinite storage life but must be mixed thoroughly before use. Room or elevated temperature cures are possible. Two-part adhesives include an epoxy monomer and amine hardener; urethanes; and peroxide-initiated adhesive systems such as vulcanized silicone, unsaturated polyesters, and acrylics. See also *one-part adhesive*.

U

UF—See *urea resin*.

U-flange—Describes shape of component perimeter incorporating a groove opposite the joint face; may be used to strengthen or aid location in the tooling.

UHMWPE—See *ultrahigh molecular weight polyethylene.*

ultimate elongation—See *elongation.*

ultimate seal strength—Maximum force that a heat-sealed thermoplastic film can sustain in a tensile test without seal failure per unit length of the seal.

ultimate tensile strength—See *tensile strength.*

ultrahigh molecular weight polyethylene—A linear carbon-chain polyethylene with molecular weight (3–5) × 10^6, prepared by Ziegler polymerization of ethylene under special conditions. It has very high wear resistance, toughness, chemical resistance, low friction coefficient, and is self lubricating, but does not melt. Processed by compression molding and ram extrusion from powdered form. Used in bearings, gears, and sliding surfaces in mining and transportation. Also called UHMWPE.

ultrasonic spot welding—An ultrasonic welding method in which the two parts are joined at localized points.

ultrasonic swaging—An assembly method in which ultrasonic energy is used to form a ring or ridge of plastic in one of the mating parts in order to capture the other part.

ultrasonic weld force—In ultrasonic welding, the force applied to the joint during the welding process. Greater than the trigger force. Intensifies the effectiveness of the colliding molecules in the joint area and provides fast thermal buildup. Must be optimized to the amplitude, generator output power, and geometry of the joint. Generally, high weld force is used with low amplitudes and low weld force with high amplitudes.

ultrasonic welding—A joining method for thermoplastics in which energy at ultrasonic frequencies (20–40 kHz) is used to produce low amplitude mechanical vibrations. The vibratory pressure at the joint interface produces frictional heat that melts the thermoplastic parts, allowing them to flow together and bond. Parts may require the use of an energy director in order to concentrate ultrasonic energy. High quality welds are easier to obtain with amorphous than with crystalline thermoplastics.

ultraviolet light—See *ultraviolet radiation.*

ultraviolet radiation—Electromagnetic radiation in the 40–400 nm wavelength region. The sun is the main natural source of UV radiation on the earth. Artificial sources are many, including fluorescent UV lamps. UV radiation causes polymer photodegradation and other chemical reactions. Note: UV light comprises a significant portion of the natural sunlight. Also called ultraviolet light, UV light, UV radiation.

ultraviolet radiation exposure—In adhesive bonding, a surface preparation technique in which the substrate is irradiated with high intensity UV light. Exposure to UV radiation results in chain scissions, crosslinking, and oxidation of the polymer surface. The effectiveness of this technique is dependent on the wavelength of radiation used. It is commonly used for polyolefins. Also called UV exposure.

underwelding—Welding procedure producing too little heating at the joint, leading to poor weld strength.

unplasticized polyvinyl chloride—Thermoplastic amorphous material often used in the building industry for applications including window frames, doors, and pipes. Also called PVC-U, rigid PVC, UPVC. See also *polyvinyl chloride.*

UPVC—See *unplasticized polyvinyl chloride.*

urea formaldehyde resin—See *urea resin.*

urea plastic—See *urea resin.*

urea resin—Thermoset resins comprised of polycondensation products of formaldehyde with urea. The urea resins have lower hardness, heat resistance, and moisture resistance than melamine resins. They are clear, colorless, and easily colored. They have higher tensile strength and hardness than phenolic resins but have lower impact strength and heat and moisture resistance. The urea resins are also scratch resistant, self-extinguishing, and solvent resistant, including hot water. They have good rigidity and electrical arc and track resistance. They must be filled for successful molding and have low resistance to long-term oxidation and to strong acids and bases. The processing is accomplished by compression and injection molding, impregnation, and coating. The applications include cosmetic container closures, appliance housings, tableware, electrical insulators, laminates for counter and table tops, adhesives, and coatings. Also called UF, urea formaldehyde resin, urea plastic.

urethane—See *nonelastomeric thermosetting polyurethane.*

urethane polymer—See *polyurethane.*

urethane resin—See *nonelastomeric thermosetting polyurethane.*

urethane thermoplastic elastomer—These thermoplastic elastomers are comprised of block polyether or polyester polyurethanes containing soft and hard domains or phases. They offer good tensile strength and elongation, service temperatures ranging from 60°F (16°C) to 250°F (121°C), excellent adhesion, and a broad hardness range. The ester based elastomers are tougher but will degrade in water in contrast to the ether based elastomers. Both types are somewhat hygroscopic and require drying prior to processing. The processing is carried out by extrusion, injection molding, film blowing, and coating. The molding requires mold release agents. The applications include tubing, water tanks, packaging film, hot-melt adhesives, soles, medical devices, conveyor belts, automotive parts, and cable jacketing. Also called polyurethane thermoplastic rubber, polyurethane TPE, PUR TPE, PU TPE, TPU, urethane thermoplastic rubber, urethane TPE.

urethane thermoplastic rubber—See *urethane thermoplastic elastomer*.

urethane TPE—See *urethane thermoplastic elastomer*.

UV absorber—A low-molecular-weight organic compound such as hydroxybenzophenone derivatives that is capable of absorbing significant amount of radiant energy in the ultraviolet wavelength region, thus protecting the material such as plastic in which it is incorporated from the damaging (degrading) effect of the energy. The absorbed energy is dissipated by the UV absorber without significant chemical change via tautomerism of hydrogen bonds. Also called UV stabilizer.

UV exposure—See *ultraviolet radiation exposure*.

UV light—See *ultraviolet radiation*.

UV radiation—See *ultraviolet radiation*.

UV stabilizer—See *UV absorber*.

V

vapor pressure curve—A curve for a substance such as water, showing the variation of boiling temperature with boiling pressure. Indicates combinations of temperature and pressure at which the substance will be in a fluid or vapor phase.

viblade welding—A variant of friction stir welding for joining thermoplastic sheets, where the heat is generated by a vibrating metal blade which traverses along the joint. See also *friction stir welding*.

vibration welding—A technique used for joining thermoplastics in which frictional heat is generated by rubbing the two parts together in a linear or angular motion. When the generated heat melts the two materials at the joint interface, vibration is terminated, and the parts are pressed together and allowed to cool. The vibratory motion is a low frequency (typically 120–240 Hz), high amplitude (0.03–0.16 inches (0.7–4.0 mm) of linear displacement), reciprocal motion. Vibration welding produces high strength bonds and is particularly suited to large parts. Also called linear friction welding.

Vicat softening point—The temperature at which a flat-ended needle of 1 mm^2 circular or square cross-section will penetrate a thermoplastic specimen to a certain depth under a specified load using a uniform rate of temperature rise. This test (ASTM D1525, ISO 306) is used for thermoplastics that have no definite melting point. Also called Vicat softening temperature.

Vicat softening temperature—See *Vicat softening point*.

vinylbenzene—See *styrene*.

vinyl ester resin—Unsaturated thermoset prepared usually by esterification of glycidyl groups of epoxy resins with unsaturated carboxylic acids. Typically, bisphenol A epoxy resins are treated with methacrylic acid and mixed with styrene reactive diluent. The resins are cured by both peroxide catalyzed addition polymerization of vinyl groups and anhydride crosslinking of hydroxy groups at room or elevated temperatures. Cured bisphenol A vinyl ester resins are characterized by chemical resistance, epoxy novolak vinyl ester resins by solvent and heat resistance, and all vinyl resins in general are tough and flexible, but shrink during cure. Processed by filament winding, transfer molding, pultrusion, coating, and lamination. Used in structural composites, coatings, sheet molding compounds, and chemical apparatus. Also called acrylic epoxy resin.

vinylidene fluoride hexafluoropropylene copolymer—Thermoplastic copolymer of vinylidene fluoride and hexafluoropropylene. Has better thermal stability; antistick, dielectric, and antifriction properties; and chemical resistance, but lower mechanical strength at room temperature and creep resistance, compared to incompletely fluorinated fluoropolymers. Processing by conventional thermoplastic techniques is difficult due to its high melt viscosity. Uses include chemical apparatus, containers, films, and coatings. See also *fluoroelastomer*.

vinylidene fluoride hexafluoropropylene tetrafluoroethylene terpolymer—Thermosetting elastomeric polymer of vinylidene fluoride, hexafluoropropylene, and tetrafluoroethylene having good chemical and heat resistance and flexibility. Used in auto parts. See also *fluoroelastomer.*

vinyl resin—A large class of thermoplastics prepared mainly by radical polymerization of vinyl monomers with or without other unsaturated monomers. The most important family of this class are vinyl chloride polymers. Other families are vinyl acetate, vinyl alcohol, vinylidene chloride, and vinyl acetal polymers. Their properties vary widely. In general, they show good weatherability, barrier properties, and flexibility, but are attacked by many solvents and have limited thermal stability. Processed by molding, extrusion, coating, and film techniques. Used very widely, especially as films and in packaging.

vinyl thermoplastic elastomer—Vinyl-alloyed thermoplastic elastomer with excellent resistance to ignition, low smoke generation, flexibility at very low temperatures, excellent dielectric properties, good toughness and elongation retention after thermal aging. Processed by extrusion and extrusion coating. Used in cable jacketing and wire coating. Also called vinyl TPE.

vinyl TPE—See *vinyl thermoplastic elastomer*.

vinyl trichloride—See *trichloroethane-1,1,2*.

viscosity—The internal resistance to flow exhibited by a fluid, the ratio of shearing stress to rate of shear. A viscosity of one poise is equal to a force of one dyne/square centimeter that causes two parallel liquid surfaces one square centimeter in area and one centimeter apart to move past one another at a velocity of one cm/second.

viscosity ratio—See *relative viscosity*.

vulcanizate—Rubber that had been irreversibly transformed from predominantly plastic to predominantly elastic material by vulcanization (chemical curing or crosslinking) using heat, vulcanization agents, accelerants, etc.

vulcanizate crosslinks—Chemical bonds formed between polymeric chains in rubber as a result of vulcanization.

vulcanization—A process in which a rubber or elastomer undergoes a change in its chemical structure, becoming less plastic, more elastic, and more resistant to swelling. An irreversible process accomplished by application of heat or reaction with sulfur or other suitable agents.

W

warpage—See *warping*.

warping—Dimensional distortion or deviation from the intended shape of a plastic or rubber article as a result of nonuniform internal stress (e.g., caused by uneven heat shrinkage). Also called warpage.

water swell—Expansion of material volume as a result of water absorption.

Weissenburg effect—The tendency of a material to flow inward. The change in normal stresses on a non-Newtonian, elastic material that causes the material to rise on the inner cylinder of two concentric, rotating cylinders, despite the centrifugal force.

weldability—The ease with which a material can be welded to give a reliable joint.

weld factor—The ratio of weld strength to strength outside the welded zone, typically determined by tensile stress tests. Also called joint efficiency, welding factor.

welding amplitude—The amplitude used in a welding process. In a vibratory motion such as in vibration or ultrasonic welding, the distance from the equilibrium position to the point of maximum displacement. Varies with welding process used and with the geometry and composition of the parts being welded.

welding by distance—A form of heated tool welding in which mechanical stops on the hot plate and holding fixtures are used to control the dimensions of the welded parts. See also *heated tool welding, welding by pressure*.

welding by pressure—A form of heated tool welding in which flow of the molten plastic after heating is regulated by application of specific pressures to the hot plate and parts. Accurate pressure control is necessary, and final part dimensions may vary due to variations in melt thickness and melt viscosity. See also *heated tool welding, welding by distance*.

welding factor—See *weld factor*.

welding frequency—The frequency used in a welding process. The number of cycles or vibrations per unit of time, usually seconds. Welding frequencies vary depending on the welding process used and on the geometry and composition of the parts being joined. Welding frequencies range from 120 and 240 Hz, used in vibration welding, to 2–10 GHz, used in microwave welding. See also *frequency*.

welding pressure—The pressure applied to the parts during welding to hold the parts in place and provide intimate contact for bonding. Welding pressure varies depending on the welding process used and the composition of the parts being joined.

welding time—A processing parameter in welding. Definition varies depending on the welding process—can refer to the time vibrations are applied to the parts being joined (ultrasonic welding), the amount of time parts are held together under pressure for cooling and solidification (heated tool welding), or both the spin time and cooling time (spin welding). Welding time is dependent on other processing parameters, such as weld amplitude, weld frequency, weld pressure, power level, temperature, etc.

wetting—The spreading out (and sometimes absorption) of a fluid onto (or into) a surface. In adhesive bonding, wetting occurs when the surface tension of the liquid adhesive is lower than the critical surface tension of the substrates being bonded. Good surface wetting is essential for high strength adhesive bonds; poor wetting is evident when the liquid beads up on the part surface. Wetting can be increased by preparation of the part surface prior to adhesive bonding.

working life—The time between mixing a two-part adhesive and the time at which the increased viscosity prohibits application of the adhesive to the part surface. Also called pot-life.

Y

yellowing—Developing of yellow color in near-white or near-transparent materials such as plastics or coatings as a result of degradation on exposure to light, heat aging, weathering, etc. Usually is measured in terms of yellow index.

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Web: www.dukcorp.com

Extol Inc.
651 Case Karsten Drive
Zeeland
MI 49464
USA
Tel: +1 616 748 9955
Web: www.extolinc.com

Forward Technology
260 Jenks Avenue
Cokato
MN 55321
USA
Tel: +1 320 286 2578
Web: www.forwardtech.com

KLN Ultraschall AG
Siegfriedstrasse 124
D-64646 Heppenheim
Germany
Tel: +49 (0) 6252 140
Web: www.kln.de

Lycro AS
N-7120 Leksvik
Norway
Tel: +47 748 54700
Web: www.lycro.com

Mecasonic UK Ltd
Unit 18
Business Centre West
Avenue One
Letchworth
Herts
SG6 2HB
UK
Tel: +44 (0) 1462 678784
Web: www.mecasonic.co.uk

Met-L-Tec, Inc.
7156 Sulier Drive
Temperance
MI 48182-9510
USA
Tel: +1 734 847 7004
Web: www.met-l-tec.com

Olsen Manufacturing Company, Inc.
4353 Delemere Boulevard
Royal Oak
MI 48073
USA
Tel: +1 248 549 4200
Web: www.olsenmfg.com

Sonics & Materials, Inc.
53, Church Hill Road
Newtown
CT 06470-1614
USA
Tel: +1 203 270 4600
Web: www.sonicsandmaterials.com

Sonitek
84 Research Drive
Milford
CT 06460
USA
Tel: +1 203 878 9321
Web: www.sonitek.com

Trinetics Group Inc.
1885 Armstrong Drive
Titusville
FL 32780
USA
Tel: +1 321 383 3456
Web: www.trineticsgroup.com

Ultra Sonic Seal
20 Turner Industrial Way
Aston
PA 19014
USA
Tel: +1 610 497 5150
Web: www.ultrasonicseal.com

Widos Wilhelm Dommer Söhne GmbH
Einsteinstrasse 5
D-71254 Ditzingen-Heimerdingen
Germany
Tel: +49 (0) 7152 99 390
Web: www.widos.de

Xfurth Ltd
Unit 4
Firbank Industrial Estate
Dallow Road
Luton
Bedfordshire
LU1 1TW
UK
Tel: +44 (0) 1582 436000
Web: www.xfurth.com

5 Radio Frequency Welding Equipment

Alloyd Company
1401 Pleasant Street
DeKalb
IL 60115
USA
Tel: +1 815 756 1623
Web: www.scapackaging.alloyd.com

Coaxial Power Systems Ltd
Spectrum House
Finmere Road
Eastbourne
East Sussex
BN22 8QL
UK
Tel: +44 (0) 1323 639974
Web: www.coaxialpower.com

Colpitt BV
Kamerlingh Onnesstraat 40
2041 CC Zandvoort
The Netherlands
Tel: +31 23 571 5941
Web: www.colpitt.nl

Cosmos Kabar
140 Schmitt Boulevard
Farmingdale
NY 11735
USA
Tel: +1 631 249 2535
Web: www.cosmos-kabar.com

F.I.A.B. HF AB
Datavägen 5
Box 10012
SE-45329 Lysekil
Sweden
Tel: +46 523 15040
Web: www.fiabhf.se

Forsstrom High Frequency AB
PO Box 55
SE-45322 Lysekil
Sweden
Tel: +46 523 66 6600
Web: www.forsstrom.com

G.E.A.F. Srl
Via Roma, 26
43030 Calestano
Parma
Italy
Tel: +39 0525 528 122
Web: www.geaf.it

High Frequency Technology Company, Inc.
172 Brook Avenue
Deer Park
NY 11729
USA
Tel: +1 800 342 3020
Web: www.rfwelding.com

Hisen Enterprises Co., Ltd
540 Wan Shou Road
Sec 1, Kueishan
Taoyuan
Taiwan
Tel: +886 2 820 90214
Web: www.hisen.com.tw

Nemeth Engineering Associates, Inc.
5901 West Highway 22
Crestwood
KY 40014
USA
Tel: +1 502 241 1502
Web: www.nemeth-engineering.com

Northwest RF Corp.
342 South Evergreen
Bensenville
IL 60106
USA
Tel: +1 630 350 4770
Web: www.northwestrf.com

Relco UK Ltd
Imperial Way
Watford
WD24 4JP
UK
Tel: +44 (0) 1923 241231
Web: www.relco.co.uk

Sanden Electronic Equipment Ltd
9/F, Block E, Mai Tak Industrial Building
221 Wai Yip Street
Kwun Tong, Kowloon
Hong Kong
Tel: +852 2345 1111
Web: www.sanden.com.hk

SEBRA
100 North Tucson Boulevard
Tucson
AZ 85716
USA
Tel: +1 520 881 6555
Web: www.sebra.com

Stanelco plc
Starpol Technology Centre
North Road
Marchwood
Southampton
SO40 4BL
UK
Tel: +44 (0) 2380 867100
Web: www.stanelco.co.uk

Thermex-Thermatron
11524 Commonwealth Drive
Louisville
KY 40299
USA
Tel: +1 502 266 5454
Web: www.thermex-thermatron.com

Weldan 2002 ApS
Granlyet 8
DK-3540 Lynge
Denmark
Tel: +45 4818 8000
Web: www.weldan.dk

Zemat Technology Group
Zeromskiego 48/50
90-626 Łódź
Poland
Tel: +4842 632 8484
Web: www.zemat.com

6 Hot Gas Welding Equipment

BAK Thermoplastic Welding Technology
Birkenweg 3
CH-6056 Kägiswil
Switzerland
Tel: +41 41 661 2250
Web: www.bak-ag.com

Demtech Services, Inc.
6414 Capitol Avenue
Diamond Springs
CA 95619
USA
Tel: +1 530 621 3200
Web: www.demtech.com

Forsthoff GmbH
Freiheitstrasse 24
D-42719 Solingen
Germany
Tel: +49 (0) 212 33 6052
Web: www.forsthoffwelding.com

HSK Kunststoff Schweisstechnik GmbH
Am Turm 9
D-53721 Siegburg
Germany
Tel: +49 (0) 2241 52727
Web: www.schweissextruder.de

Kamweld Technologies, Inc.
90 Access Road
Norwood
MA 02062
USA
Tel: +1 781 762 6922
Web: www.kamweld.com

Laramy Products LLC
PO Box 1168
40, Sandy Lane
Lyndonville
VT 05851
USA
Tel: +1 802 626 9328
Web: www.laramyplasticwelders.com

Leister Process Technologies
Riedstrasse
CH-6060 Sarnen
Switzerland
Tel: +41 41 662 7474
Web: www.leister.com

Seelye-Eiler Industrial Plastic Products
9700 Newton Avenue South
Bloomington
MN 55431
USA
Tel: +1 952 881 2658
Web: www.seelyeplastics.com

Steinel Vertrieb GmbH
Dieselstrasse 80-84
D-33442 Herzebrock-Clarholz
Germany
Tel: +49 (0) 5245 4480
Web: www.steinel.de

Tempatron Ltd
5 Darwin Close
Reading
Berkshire
RG2 0TB
UK
Tel: +44 (0) 118 931 4062
Web: www.tempatron.co.uk

Vulkan AG
Trischlistrasse 23
CH-9400 Rorschach
Switzerland
Tel: +41 (0) 71 844 7888
Web: www.vulkanag.ch

Wegener GmbH
Vaalserstrasse 81
D-52074 Aachen
Germany
Tel: +49 (0) 241 705 2215
Web: www.wegenerwelding.de

Zinser Schweisstechnik GmbH
Daimlerstrasse 4
D-73095 Albershausen
Germany
Tel: +49 (0) 7161 5050
Web: www.zinser.de

7 Extrusion Welding Equipment

BAK Thermoplastic Welding Technology
Birkenweg 3
CH-6056 Kägiswil
Switzerland
Tel: +41 41 661 2250
Web: www.bak-ag.com

Bauku GmbH
Industriegelände 9
D-51674 Wiehl
Germany
Tel: +49 (0) 2262 72070
Web: www.bauku.de

Demtech Services, Inc.
6414 Capitol Avenue
Diamond Springs
CA 95619
USA
Tel: +1 530 621 3200
Web: www.demtech.com

Dohle Extrusiontechnik GmbH
Eitorferstrasse 1
D-53809 Ruppichteroth
Germany
Tel: +49 (0) 2295 902960
Web: www.dohle-extruder.de

Drader Injectiweld Inc.
5750 50th Street, N.W.
Edmonton
Alberta T6B 2Z8
Canada
Tel: +1 780 440 2231
Web: www.drader.com

HSK Kunststoff Schweisstechnik GmbH
Am Turm 9
D-53721 Siegburg
Germany
Tel: +49 (0) 2241 52727
Web: www.schweissextruder.de

KWH Pipe Ltd
PO Box 21
FI-65101 Vaasa
Finland
Tel: +358 6 326 5511
Web: www.kwhpipe.com

Leister Process Technologies
Riedstrasse
CH-6060 Sarnen
Switzerland
Tel: +41 41 662 7474
Web: www.leister.com

Munsch Kunststoff-Schweisstechnik GmbH
Im Staudchen
D-56235 Ransbach-Baumbach
Germany
Tel: +49 (0) 26 238 9880
Web: www.munsch-kunststoff-schweisstechnik.de

Ritmo SpA
Via Volta 7
35033 Bresseo (Padova)
Italy
Tel: +39 049 99 01 888
Web: www.ritmo.it

Wegener GmbH
Vaalserstrasse 81
D-52074 Aachen
Germany
Tel: +49 (0) 241 705 2215
Web: www.wegenerwelding.de

Wil-Key International Sdn. Bhd.
18, Jalan Industri USJ 1/14
Taman Industrian USJ 1
47610 Subang Jaya
Malaysia
Tel: +603 8024 0612
Web: www.wil-key.com.my

8 Laser Welding Equipment

Bielomatik Leuze GmbH & Co. KG
Daimlerstrasse 6-10
D-72639 Neuffen
Germany
Tel: +49 (0) 7025 120
Web: www.bielomatik.com

Branson Ultrasonics Corp.
41 Eagle Road
Danbury
CT 06813-1961
USA
Tel: +1 203 796 0400
Web: www.bransonultrasonics.com

Carl Baasel Lasertechnik GmbH & Co. KG
Petersbrunnerstrasse 1b
D-82319 Starnberg
Germany
Tel: +49 (0) 8151 7760
Web: www.rofin.com

Control Micro Systems
4420 Metric Drive
Winter Park
FL 32792
USA
Tel: +1 407 679 9716
Web: www.plastic-laser-welding.com

Dukane Intelligent Assembly Solutions
2900 Dukane Drive
St. Charles
IL 60174
USA
Tel: +1 630 797 4900
Web: www.dukcorp.com

Fisba Optik AG
Rorschacherstrasse 268
CH-9016 St Gallen
Switzerland
Tel: +41 (0) 71 282 3131
Web: www.fisba.ch

Jenoptik Laser Technologies
8020 Kensington Court
Brighton
MI 48116
USA
Tel: +1 248 446 9540
Web: www.lasertechnologies-jenoptik.com

Laser Lines Ltd
Beaumont Close
Banbury
Oxon
OX16 1TH
UK
Tel: +44 (0) 1295 672500
Web: www.laserlines.co.uk

Leister Process Technologies
Riedstrasse
CH-6060 Sarnen
Switzerland
Tel: +41 41 662 7474
Web: www.leister.com

LPKF Laser & Electronics AG
Plastics Welding Division
Gundstrasse 15
D-91056 Erlangen
Germany
Tel: +49 (0) 9131 616570
Web: www.laserquipment.com

Prolas GmbH
St. Jobser-Strasse 53
D-52146 Würselen
Germany
Tel: +49 (0) 2405 47170
Web: www.prolas.de

Sonotronic Nagel GmbH
Becker-Göring-Strasse 17
D-76307 Karlsbad-Ittersbach
Germany
Tel: +49 (0) 7248 91 660
Web: www.sonotronic.com

SPI Lasers
3 Wellington Park
Tollbar Way
Hedge End
Southampton
SO30 2QU
UK
Tel: +44 (0) 1489 779696
Web: www.spilasers.com

9 Infrared Welding Equipment

Agru Kunststofftechnik GmbH
A-4540 Bad Hall
Austria
Tel: +43 (0) 7258 7900
Web: www.agru.at

Forward Technology
260 Jenks Avenue
Cokato
MN 55321
USA
Tel: +1 320 286 2578
Web: www.forwardtech.com

Georg Fischer Piping Systems Ltd
CH-8201 Schaffhausen
Switzerland
Tel: +41 (0) 52 631 1111
Web: www.piping.georgfischer.com

Heraeus Noblelight
I-R Division
Unit 1, Millennium Court
Clayhill Industrial Estate
Buildwas Road
Neston
Cheshire
CH64 3UZ
UK
Tel: +44 (0) 151 353 2710
Web: www.heraeus-noblelight.com

Simtech Industrial Products
47a Runway Road
Bristol Industrial Park
Levittown
PA 19057
USA
Tel: +1 215 547 0444
Web: www.simtechusa.com

Trinetics Group Inc.
1885 Armstrong Drive
Titusville
FL 32780
USA
Tel: +1 321 383 3456
Web: www.trineticsgroup.com

Widos Wilhelm Dommer Söhne GmbH
Einsteinstrasse 5
D-71254 Ditzingen-Heimerdingen
Germany
Tel: +49 (0) 7152 99 390
Web: www.widos.de

10 Resistive Implant Welding Equipment

Agru Kunststofftechnik GmbH
A-4540 Bad Hall
Austria
Tel: +43 (0) 7258 7900
Web: www.agru.at

Caldervale Technology Ltd
Bretfield Court
Bretton Street Industrial Estate
Dewsbury
West Yorkshire
WF12 9DB
UK
Tel: +44 (0) 1924 469571
Web: www.caldertech.com

Fusion Group plc
Smeckley Wood Close
Chesterfield Trading Estate
Chesterfield
S41 9PZ
UK
Tel: +44 (0) 1246 455 998
Web: www.fusiongroup.co.uk

Georg Fischer Piping Systems Ltd
CH-8201 Schaffhausen
Switzerland
Tel: +41 (0) 52 631 1111
Web: www.piping.georgfischer.com

J Sauron SA
19 Rue Pierre Josse
Z.I. Les Bordes
CE 2413
91924 Bondoufle Cedex
France
Tel: +33 (0) 169 91 4800
Web: www.j-sauron.com

KWH Pipe Ltd
PO Box 21
FI-65101 Vaasa
Finland
Tel: +358 6 326 5511
Web: www.kwhpipe.com

MSA Engineering Systems Ltd
3 Assured Drive
Thurmaston
Leicester
LE4 8BB
UK
Tel: +44 (0)116 260 8866
Web: www.msa-engineering.co.uk

PF-Schweisstechnologie GmbH
Karl-Broeger-Strasse 10
D-36304 Alsfeld
Germany
Tel: +49 (0) 6631 96520
Web: www.pf-schweisstechnologie.de

11 Induction Welding Equipment

Emabond Solutions
49 Walnut Street
Norwood
NJ 07648
USA
Tel: +1 201 767 7400
Web: www.emabond.com

Lepel Corp.
730 Larry Court
Waukesha
WI 53186
USA
Tel: +1 262 782 0450
Web: www.cap-sealing.com

Relco UK Ltd
Imperial Way
Watford
WD24 4JP
UK
Tel: +44 (0) 1923 241231
Web: www.relco.co.uk

Sonotronic Nagel GmbH
Becker-Göring-Strasse 17
D-76307 Karlsbad-Ittersbach
Germany
Tel: +49 (0) 7248 91 660
Web: www.sonotronic.com

12 Heat Sealing Equipment

Aline Heat Seal Corp.
13844 Struikman Road
Cerritos
CA 90703
USA
Tel: +1 562 229 9727
Web: www.alinesys.com

Alloyd Company
1401 Pleasant Street
DeKalb
IL 60115
USA
Tel: +1 815 756 1623
Web: www.scapackaging.alloyd.com

Audion Elecktro
Hogeweyselaan 235
1382 JL Weesp
The Netherlands
Tel: +31 (0) 294 491717
Web: www.audion.com

Cibra Nova snc
Via Brescia 16
20063 Cernusco sul Naviglio (Milano)
Italy
Tel: +39 02 9210 4927
Web: www.cibra.it

Clamco Corp.
12900 Plaza Drive
Cleveland
OH 44130
USA
Tel: +1 216 267 1911
Web: www.clamcocorp.com

Colpitt BV
Kamerlingh Onnesstraat 40
2041 CC Zandvoort
The Netherlands
Tel: +31 23 571 5941
Web: www.colpitt.nl

Hawo GmbH
Obere Au 2-4
D-74847 Obrigheim
Germany
Tel: +49 (0) 6261 97700
Web: www.hawo.com

Healey Packaging Ltd
22 Bartel Close
Hemel Hempstead
Herts
HP3 8LX
UK
Tel: +44 (0)1442 244771
Web: www.healeypackaging.co.uk

Hulme Martin Heat Sealers Ltd
Unit 5B
Country Business Centre
White Cottage Farm
Lucas Green Road
Woking
Surrey
GU24 9LZ
UK
Tel: +44 (0) 1483 476767
Web: www.hulmemartin.co.uk

Kettenbaum Folienschweisstechnik GmbH & Co. KG
Asselborner Weg 14-16
D-51429 Bergisch-Gladbach
Germany
Tel: +49 (0) 2204 8390
Web: www.folienschweisstechnik.com

Packaging Aids Corp./Vertrod
25 Tiburon Street
San Rafael
CA 94901
USA
Tel: +1 415 454 4868
Web: www.pacmachinerygroup.com

Packaging Automation Ltd
Parkgate Industrial Park
Knutsford
Cheshire
WA16 8XW
UK
Tel: +44 (0) 1565 75500
Web: www.pal.co.uk

Rische + Herfurth GmbH
Kedenburgstrasse 53-59
D-22041 Hamburg
Germany
Tel: +49 (0) 4065 69030
Web: www.polystar-hamburg.de

Sanden Electronic Equipment Ltd
9/F, Block E, Mai Tak Industrial Building
221 Wai Yip Street
Kwun Tong, Kowloon
Hong Kong
Tel: +852 2345 1111
Web: www.sanden.com.hk

S-DAI Industrial Co. Ltd
32, Alley 16
Lane 418
Chien-Te St
East District Taichung
Taiwan
Tel: +886 4 2283 3456
Web: www.s-dai.com.tw

Thermal Press International, Inc.
341 Stealth Ct.
Livermore
CA 94551
USA
Tel: +1 925 454 9800
Web: www.thermalpress.com

Widmann Maschinen Vertriebs GmbH
Siemensstrasse 19
D-73278 Schlierbach
Germany
Tel: +49 (0) 7021 97330
Web: www.widmann-maschinen.de

Zed Industries, Inc.
PO Box 458
3580 Lightner Road
Vandalia
OH 45377
USA
Tel: +1 937 667 8407
Web: www.zedindustries.com

13 Flash-Free Welding Equipment

Agru Kunststofftechnik GmbH
A-4540 Bad Hall
Austria
Tel: +43 (0) 7258 7900
Web: www.agru.at

Engiplast Inc.
105 River Oaks Drive
PO Box 1023
Gatesville
TX 76528
USA
Tel: +1 254 865 9444
Web: www.engiplastinc.com

Georg Fischer Piping Systems Ltd
CH-8201 Schaffhausen
Switzerland
Tel: +41 (0) 52 631 1111
Web: www.piping.georgfischer.com

14 Adhesive Suppliers

3M
Industrial Tape and Specialities Division
3M Center, Building 220-7E-01
St. Paul
MN 55144-1000
USA
Tel: +1 888 364 3577
Web: www.3m.com

Ablestik
20021 Susana Road
Rancho Dominguez
CA 90221
USA
Tel: +1 310 764 4600
Web: www.ablestik.com

Adhesives Research, Inc.
400 Seaks Run Road
PO Box 100
Glen Rock
PA 17327
USA
Tel: +1 717 235 7979
Web: www.adhesivesresearch.com

Apollo Chemicals Ltd
Sandy Way
Amington Industrial Estate
Tamworth
Staffordshire
B77 4DS
UK
Tel: +44 (0) 1827 54281
Web: www.apolloadhesives.com

Atlas Minerals & Chemicals, Inc.
PO Box 38
1227 Valley Road
Mertztown
PA 19539
USA
Tel: +1 610 682 7171
Web: www.atlasmin.com

Avery Dennison
Speciality Tape Division
250 Chester Street - #5M
Painesville
OH 44077
USA
Tel: +1 440 358 3256
Web: www.averydennison.com

Bacon Industries, Inc.
192 Pleasant Street
Watertown
MA 02472
USA
Tel: +1 617 926 2550
Web: www.baconindustries.com

Beacon Adhesives, Inc.
125 MacQuesten Parkway South
Mount Vernon
NY 10550
USA
Tel: +1 914 699 3400
Web: www.beacon1.com

Beardow Adams
32 Blundells Road
Bradville
Milton Keynes
MK13 7HF
UK
Tel: +44 (0) 1908 574000
Web: www.beardowadams.com

Bluestar Silicones
21, Avenue Georges Pompidou
69003 Lyon 03
France
Tel: +33 4 72 13 19 00
Web: www.bluestarsilicones.com

Bostik, Inc.
11320 Watertown Plank Road
Wauwatosa
WI 53226-3434
USA
Tel: +1 800 558 4302
Web: www.bostik.com

Caswell Adhesives
6 Princewood Road
Earlstrees Industrial Estate
Corby
Northamptonshire
NN17 4AP
UK
Tel: +44 (0) 1536 464800
Web: www.caswell-adhesives.co.uk

Ciba Speciality Chemicals
540 White Plains Road
PO Box 2005
Tarrytown
NY 10591-9005
USA
Tel: +1 914 785 2000
Web: www.cibasc.com

Dow Automotive
1250 Harmon Road
Auburn Hills
MI 48362
USA
Tel: +1 248 391 6300
Web: www.dow.com/automotive

Dow Corning Corp.
3901 South Saginaw Road
Midland
MI 48640-0994
USA
Tel: +1 989 496 4400
Web: www.dowcorning.com

Dymax Corp.
318 Industrial Lane
Torrington
CT 06790
USA
Tel: +1 860 482 1010
Web: www.dymax.com

Epoxies, Etc
Starline Way
Cranston
RI 02921
USA
Tel: +1 401 946 5564
Web: www.epoxies.com

H.B. Fuller Company
1200 Willow Lake Boulevard
St. Paul
MN 55164-0683
USA
Tel: +1 651 236 5900
Web: www.hbfuller.com

Henkel KGaA
Henkelstrasse 67
D-40589 Düsseldorf
Germany
Tel: +49 (0) 211 7970
Web: www.henkel.com

Huntsman Advanced Materials
Everslaan 45
B-3078 Everberg
Belgium
Tel: +32 (0) 2 758 9211
Web: www.huntsman.com/advanced_materials

ITW Devcon
30 Endicott Street
Danvers
MA 01923
USA
Tel: +1 800 933 8266
Web: www.devcon.com

Klebchemie M.G. Becker GmbH & Co. KG
Max-Becker-Strasse 4
D-76356 Weingarten
Baden
Germany
Tel: +49 (0) 7244 620
Web: www.kleiberit.com

Leech Products, Inc.
PO Box 2147
Hutchinson
KS 67504-2147
USA
Tel: +1 620 669 0145
Web: www.leechadhesives.com

Lohmann GmbH & Co. KG
Irlicher Strasse 55
D-56567 Neuwied
Germany
Tel: +49 (0) 2631 340
Web: www.lohmann-tapes.com

Lord Corp.
111 Lord Drive
PO Box 8012
Cary
NC 27512-8012
USA
Tel: +1 919 468 5979
Web: www.lordadhesives.com

Master Bond, Inc.
154 Hobart Street
Hackensack
NJ 07601
USA
Tel: +1 201 343 8983
Web: www.masterbond.com

Momentive Performance Materials
187 Danbury Road
Wilton
CT 06897
USA
Tel: +1 607 786 8131
Web: www.momentive.com

National Starch and Chemical Company
10 Finderne Avenue
PO Box 6500
Bridgewater
NJ 08807-3300
USA
Tel: +1 800 797 4992
Web: www.nationalstarch.com

Permabond Engineering Adhesives Ltd
Wessex Business Park
Wessex Way
Colden Common
Winchester
Hampshire
SO21 1WP
UK
Tel: +44 (0)1962 711661
Web: www.permabond.com

Permalite Plastics Corp.
1131 West Baker Street
Costa Mesa
CA 92626
USA
Tel: +1 714 548 1137
Web: www.permaliteplastics.com

Rohm and Haas
100 Independence Mall West
Philadelphia
PA 19106
USA
Tel: +1 877 288 5881
Web: www.rohmhaas.com

Synthetic Surfaces, Inc.
PO Box 241
Scotch Plains
NJ 07076-0241
USA
Tel: +1 908 233 6803
Web: www.nordot.com

Tra-Con, Inc.
45 Wiggins Avenue
Bedford
MA 01730
USA
Tel: +1 800 872 2661
Web: www.tra-con.com

15 Mechanical Fasteners and Mechanical Fastening Equipment

ATM Automation Ltd
Blaby Industrial Park
Winchester Avenue
Blaby
Leicestershire
LE8 4GZ
UK
Tel: +44 (0) 116 277 3607
Web: www.atmautomation.com

BalTec Corp.
130 Technology Drive
Canonsburg
PA 15317
USA
Tel: +1 724 873 5757
Web: www.baltecorporation.com

Branson Ultrasonics Corp.
41 Eagle Road
Danbury
CT 06813-1961
USA
Tel: +1 203 796 0400
Web: www.bransonultrasonics.com

Dukane Intelligent Assembly Solutions
2900 Dukane Drive
St. Charles
IL 60174
USA
Tel: +1 630 797 4900
Web: www.dukcorp.com

Emhart Fastening Teknologies
Automotive Division
PO Box 868
Mt Clemens
MI 48046
USA
Tel: +1 586 949 0440
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Index