1 Introduction to Creep, Polymers, Plastics and Elastomers

1.1 Introduction

In an earlier book of this series, *The Effect of Temperature and Other Factors on Plastics and Elastomers* [1], the general mechanical properties of plastics were discussed. The mechanical properties as a function of temperature, humidity, and other factors were presented in graphs or tables. That work includes hundreds of graphs of stress versus strain, modulus versus temperature, and impact strength versus temperature. However, when one starts designing products made of plastic, these graphs do not supply all the necessary information. This is because these graphs show the results of relatively short-term tests. The value in design is in the initial selection of materials in terms of stiffness, strength, etc. Designs based on that short-term data obtained from a short-term test would not predict accurately the long-term behavior of plastics. This is partly because plastics are viscoelastic materials. Viscoelastic by definition means possessing properties that are both solid-like and liquid-like. More precisely in reference to plastics, viscoelastic means that measurements such as modulus, impact strength, and coefficient of friction (COF) are not only sensitive to straining rate, temperature, humidity, etc. but also to elapsed time and loading history. The manufacturing method used for the plastic product can also create changes in the structure of the material which have a pronounced effect on properties.

The rest of this chapter first deals with the types of stress and a short introduction to creep. Then the chemistry of plastics is discussed and because plastics are polymeric materials the focus is more on polymer chemistry. The discussion includes polymerization chemistry and the different types of polymers and how they can differ from each other. Since plastics are rarely "neat," reinforcement, fillers, and additives are reviewed. This is followed by a detailed look at creep, including creep-specific tests and creep graphs. The discussion takes a look at what happens at the microscopic level when plastics exhibit creep.

1.2 Types of Stress

Creep is the time-dependent change in the dimensions of a plastic article when subjected to a constant stress. Stress can be applied in a number of ways. Normal stress (σ) is the ratio of the applied force (F) over the cross-sectional area (A) as shown in Eq. (1.1).

$$\sigma = \frac{F}{A} \tag{1.1}$$

1.2.1 Tensile and Compressive Stress

When the applied force is applied directed away from the part, as shown in Figure 1.1, it is a tensile force inducing a tensile stress. When the force is applied toward the part it is a compressive force inducing a compressive stress.

1.2.2 Shear Stress

Shear stress (τ) is also expressed as force per unit area as in Eq. (1.2).

The shear force is applied parallel to the cross-sectional area "A" as shown in Figure 1.2.

1.2.3 Torsional Stress

Torsional stress (τ) occurs when a part such as a rod for shaft is twisted as in Figure 1.3. This is also a shear stress, but the stress is variable and depends how far the point of interest is from the center of the shaft. The equation describing this is shown in Eq. (1.2).

McKeen: The Effect of Creep and other Time Related Factors on Plastics and Elastomers.
DOI: http://dx.doi.org/10.1016/B978-0-323-35313-7.00001-8

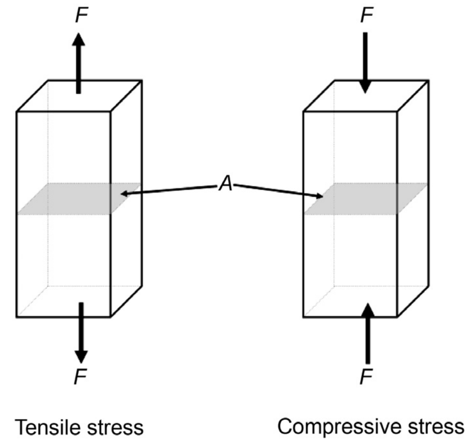


Figure 1.1 Illustration of tensile stress and compressive stress.

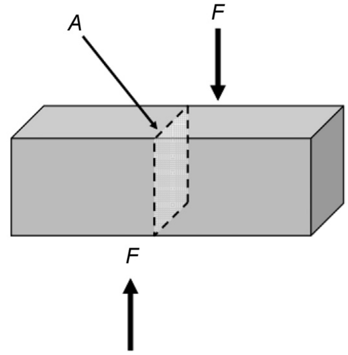


Figure 1.2 Illustration of shear stress.

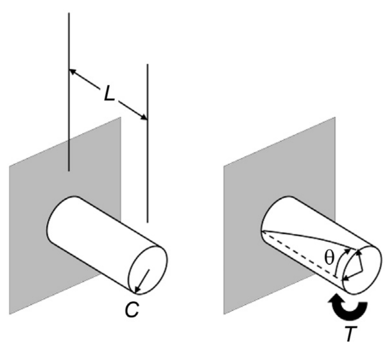


Figure 1.3 Illustration of torsional stress.

$$\tau = \frac{Tc}{K} \tag{1.2}$$

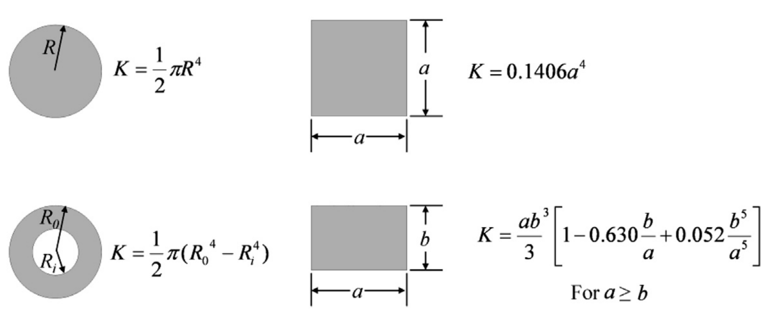
In this equation, T is the torque and c is the distance from the center of the shaft or rod. K is a torsional constant that is dependent on the geometry of the shaft, rod, or beam. The torque (T) is further defined by Eq. (1.3), in which θ is the angle of twist, G is the modulus of rigidity (material dependent), and L is the length.

$$T = \frac{\theta KG}{L} \tag{1.3}$$

The torsional constant (K) is dependent upon geometry and the formulas for several geometries are shown in Figure 1.4. Additional formulas for torsional constant are published [2, pp. 63–76].

1.2.4 Flexural or Bending Stress

Bending stress or flexural stress commonly occurs in two instances, shown in Figure 1.5. One is called a simply supported structural beam bending and the other is called cantilever bending. For the simply supported structural beam, the upper surface of the bending beam is in compression and the bottom surface is in tension. NA is a region of zero stress. The bending stress (σ) is defined by Eq. (1.4). M is the bending moment, which is calculated by multiplying a force by the distance between that point of interest and the force. c is the distance from NA (Figure 1.5) and I is the moment of inertia. The cantilevered beam configuration is also shown in Figure 1.5 and has a similar formula. The formulas for M, c, and I can be complex, depending on the exact configuration and beam shape, but many are published [2, pp. 46–53, 547–555].



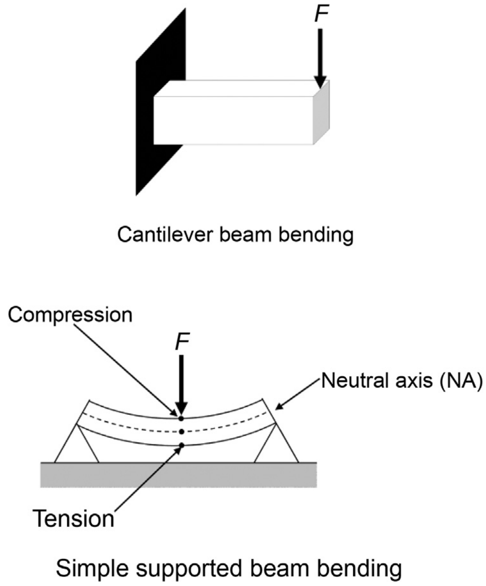


Figure 1.5 Illustration of flexural or bending stress.

Figure 1.6 Picture of a three point flexural or bending test being done in an Instron universal testing machine [3].

A picture of a supported beam bending test in an Instron is shown in Figure 1.6.

$$\sigma = \frac{Mc}{I} \tag{1.4}$$

1.2.5 Hoop Stress

Hoop stress (σ_h) is mechanical stress defined for rotationally symmetric objects such as pipe or tubing. The real world view of *hoop stress* is the tension applied to the iron bands, or hoops, of a

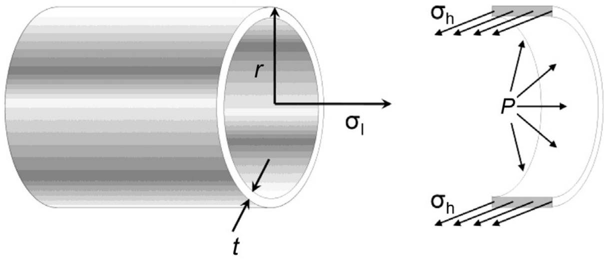


Figure 1.7 Illustration of hoop stress.

circumferentially. Figure 1.7 shows stresses caused by pressure (P) inside a cylindrical vessel. The hoop stress is indicated in the right side of Figure 1.7 that shows a segment of the pipe.

The classic equation for hoop stress created by an internal pressure on a thin wall cylindrical pressure vessel is given in Eq. (1.5):

$$\sigma_h = \frac{Pr}{t} \tag{1.5}$$

where:

P = the internal pressure

t = the wall thickness

r = is the radius of the cylinder.

The SI unit for P is Pascal (Pa), while t and r are in meters (m).

If the pipe is closed on the ends, any force applied to them by internal pressure will induce an *axial or longitudinal stress* (σ_l) on the same pipe wall. The longitudinal stress under the same conditions of Figure 1.7 is given by Eq. (1.6)

$$\sigma_l = \frac{\sigma_h}{2} \tag{1.6}$$

There could also be a radial stress especially when the pipe walls are thick, but thin-walled sections often have negligibly small *radial stress* (σ_r). The stress in radial direction at a point in the tube or cylinder wall is shown in Eq. (1.7).

$$\sigma_r = \left(\frac{a^2P}{b^2 - a^2}\right)\left(1 - \frac{b^2}{r^2}\right) \tag{1.7}$$

where:

P = internal pressure in the tube or cylinder

b = external radius of tube or cylinder

r = radius to point in tube where radial stress is calculated.

Often the stresses in pipe are combined into a measure called *equivalent stress*. This is determined using the Von Mises equivalent stress formula which is shown in Eq. (1.8):

$$\sigma_e = \sqrt{\sigma_l^2 + \sigma_h^2 - \sigma_l\sigma_h + 3\tau_c^2} \qquad (1.8)$$

where:

σ_l = longitudinal stress

σ_h = hoop stress

τ_c = tangential shear stress (from material flowing through the pipe).

Failure by fracture in cylindrical vessels is dominated by the hoop stress in the absence of other external loads because it is the largest principal stress. Failure by yielding is affected by an equivalent stress that includes hoop stress, and longitudinal stress. The equivalent stress can also include tangential shear stress and radial stress when present.

1.3 Basic Concepts of Creep

As noted earlier, creep is the time-dependent change in the dimensions of a plastic article when subjected to a constant stress. Metals also possess creep properties, but at room temperature the creep behavior of metals is usually negligible. Therefore, metal design procedures are simpler because the modulus may be regarded as a constant (except at high temperatures). However, the modulus of a plastic is not a constant. Provided its variation is known then the creep behavior of plastics can be compensated for using accurate and well-established design procedures or by modification of the plastics composition with reinforcing fillers. For metals, the objective of the design method is usually to determine stress values which will not cause fracture. However, for plastics it is more likely that excessive deformation will be the limiting factor in the selection of working stresses. This book looks specifically at the deformation behavior of plastics.

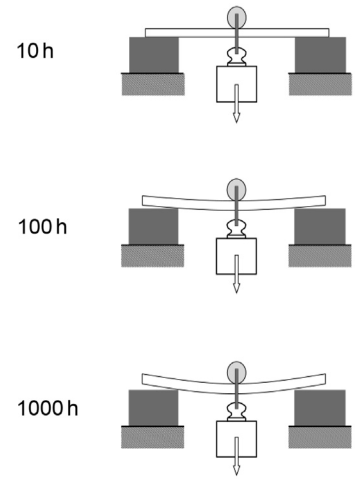


Figure 1.8 Illustration of flexural creep.

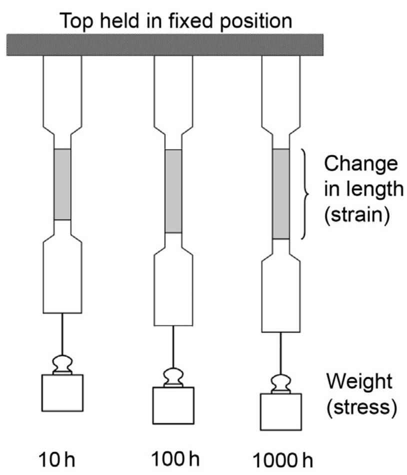


Figure 1.9 Illustration of tensile creep.

Creep is the time-dependent change in the dimensions of a plastic article when subjected to stress. This is shown schematically in Figure 1.8 for flexural creep. A given load is shown on a plastic plaque supported at the ends. The weight or load along with gravity supplies a constant stress on the plastic plaque. After 10 h in this condition there is very little deflection or sagging of the plastic plaque. However, after 100 h the deflection, or strain, has increased. It is deflected even further after 1000 h. The creep measured by the method in Figure 1.9 is called tensile creep. If the force squeezes on the plastic plaque then the creep measure would be compressive creep.

If one plots the deflection versus time a plot like the first part (A–B) of that shown in Figure 1.10 might be obtained. If the stress (or weight) is removed at point B, the strain or deflection

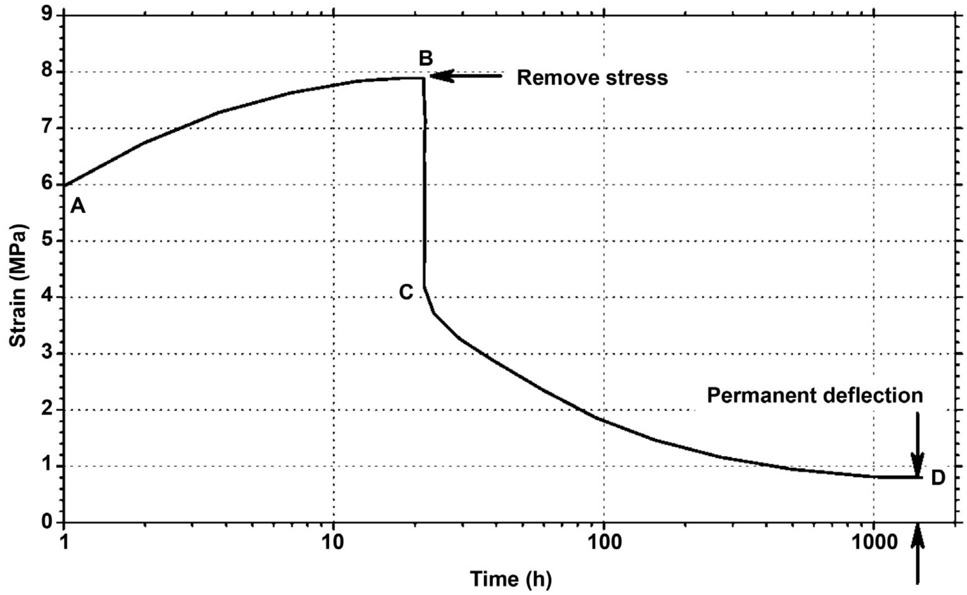


Figure 1.10 Illustration of elastic recovery, viscous recovery and permanent deflection or creep.

recovers partially very rapidly to point C. That part is called the elastic recovery. After point C, there is a slow viscous recovery to some final point D. The plaque is no longer flat and that remaining deflection is permanent. Creep is the permanent deformation resulting from prolonged application of stress below the elastic limit.

Creep and other creep-related properties (discussed later) are among the most important mechanical characteristics of plastics. Plastics that have significant time sensitivity at use temperature will have limited value for structural applications or applications demanding dimensional stability.

1.3.1 Categories, Stages, or Regions of Creep

When one does a tensile creep experiment, such as that shown in Figure 1.9, and the data are graphed, a plot like that shown in Figure 1.11 may be obtained. Creep data in this plot can be subdivided into three categories (also called stages or regions): primary, steady state, and tertiary creep. These occur sequentially as shown in Figure 1.11. Initially, when the stress is applied, there is an initial strain which is an elastic component to the strain. For that portion, if the stress is removed the material returns to its original shape and dimensions. Considering that the slope of the curve gives the strain rate, the three categories correspond to a decreasing strain rate (primary), approximately constant strain rate (steady state) and increasing strain rate (tertiary).

The first stage of creep shown in Figure 1.11 is named the primary creep region, but it is also known as transient creep stage. Primary creep strain is often less than 1% of the sum of the elastic, steady state, and primary strains. The second stage of creep shown in Figure 1.11 is the steady state region or secondary creep. This region is so named because the strain rate is constant.

When the amount of strain is high creep fracture or rupture will occur. This is called the tertiary region and is also known as accelerating creep stage. The high strains in this region will start to cause necking or other failure in the material. Necking will cause an increase in the local stress of the component that further accelerates the strain. The importance of the tertiary region to normal operation and creep design criteria is minimal, as plastic parts are designed to avoid this region as failure is imminent. In Figure 1.11, the timescale of the tertiary region is greatly expanded for the purpose of clarity. Considering the small amount of time in addition to the fact that the tertiary region develops a plastic instability similar to necking, operating in the tertiary region is not feasible. Therefore, it is a conservative estimate to approximate the end of serviceable life of any component to coincide with the end of the steady state creep region.

Whether these regions have any significance other than as arbitrary divisions of the curve is an arguable

DOCKET ALARM

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.

WHAT WILL YOU BUILD? | **sales@docketalarm.com** | **1-866-77-FASTCASE**

fastcase®
Smarter legal research.