UNITED STATES DISTRICT COURT
DISTRICT OF MINNESOTA

STRATASYS INC. Plaintiff, v. MICROBOARDS TECHNOLOGY, LLC d/b/a AFINIA Defendant.	)	Case No. _____________ **COMPLAINT AND** **DEMAND FOR JURY TRIAL**

COMPLAINT FOR PATENT INFRINGEMENT

Plaintiff Stratasys Inc., for its Complaint against Defendant Microboards Technology, LLC d/b/a Afinia, alleges as follows:

PARTIES

1. Plaintiff Stratasys Inc. ("Stratasys") is a Delaware corporation with a principal place of business at 7665 Commerce Way, Eden Prairie, Minnesota 55344.

2. On information and belief, Defendant Microboards Technology, LLC is a Minnesota limited liability company with a principal place of business at 8150 Mallory Court, Chanhassen, Minnesota 55317 and conducts business relevant to this action through its unincorporated division known as Afinia. The defendant is hereinafter referred to as Afinia.

JURISDICTION AND VENUE

3. This is an action for patent infringement arising under the patent laws of the United States, 35 U.S.C. § 1 et seq.

4. This Court has subject matter jurisdiction over this action under 28 U.S.C. §§ 1331 and 1338(a).

5. The Court has both general and specific personal jurisdiction over Afinia. On information and belief, Afinia transacts business and has continuous and systematic contacts in this District, maintains an ongoing presence within the District, and has committed acts of patent infringement in this District.

6. Venue is proper in this judicial district under 28 U.S.C. §§ 1391(b) and (c) and 1400(b).

FACTS

7. Stratasys was founded in 1989 by Steven Scott Crump, an engineer and inventor, and Lisa H. Crump to capitalize on Mr. Crump's invention of Fused Deposition Modeling, which is an additive manufacturing process that prints three dimensional ("3D") objects from computer models by building up layers of one or more extruded materials onto a platform using a device that has come to be generally known as a 3D printer. Stratasys has commercialized this technology in its FDM® 3D printers and production systems.

8. Stratasys has grown from a small start-up to be the worldwide leader in sales of 3D printers. The Stratasys FDM® printers and systems are used for prototyping, design,

and manufacturing purposes, and are used extensively in engineering, aerospace, automotive, medical, education, and many other industries and applications.

9. Stratasys has invested millions of dollars in improving its FDM® technology over the past two and a half decades since its inception, and has numerous patents covering advancements in Fused Deposition Modeling devices and methods.

10. In 2012, Stratasys Inc. merged with Objet Ltd. of Rehovot, Israel to form the corporate entity Stratasys Ltd. (Nasdaq: SSYS). Today, Stratasys Ltd. and its subsidiaries, including Stratasys Inc. and MakerBot Industries, have more than 1500 employees, hold more than 500 granted or pending additive manufacturing patents globally, and have received numerous awards for technology and leadership.

11. In recent years, other companies have begun to make and sell 3D printers that incorporate features and capabilities involving the extrusion of materials in additive layers to form 3D objects. For example, by 2011, a Chinese company began making and selling the UP! printer. On information and belief, the UP! printer is sold in the United States through direct sales over the Internet, through resellers, and through original equipment manufacturers who rebrand and repackage imported UP! printers under their own name and may add features or enhancements to the printer.

12. On information and belief, Afinia began selling a rebranded and repackaged UP! printer as the Afinia H-Series 3D Printer at least by 2012. Afinia sells the Afinia H-Series 3D Printer at least through its website (www.afinia.com) and online retailers. Afinia also makes available and distributes marketing, instructional, and support materials to customers through its website. Afinia also maintains a technical support staff that

provides support to customers, including through Afinia's website and by email and telephone.

PATENTS IN SUIT

13. On August 5, 1997, U.S. Patent No 5,653,925 ("the '925 patent") entitled "METHOD FOR CONTROLLED POROSITY THREE-DIMENSIONAL MODELING," was duly and lawfully issued by the United States Patent and Trademark Office. Stratasys was assigned and continues to hold all right, title, and interest in the '925 patent. A true and correct copy of the '925 patent is attached as Exhibit A to this Complaint.

14. On February 2, 1999, U.S. Patent No. 5,866,058 ("the '058 patent"), entitled "METHOD FOR RAPID PROTOTYPING OF SOLID MODELS," was duly and lawfully issued by the United States Patent and Trademark Office. Stratasys was assigned and continues to hold all right, title, and interest in the '058 patent. A true and correct copy of the '058 patent is attached as Exhibit B to this Complaint.

15. On December 21, 1999, U.S. Patent No. 6,004,124 ("the '124 patent"), entitled "THIN-WALL TUBE LIQUIFIER," was duly and lawfully issued by the United States Patent and Trademark Office. Stratasys was assigned and continues to hold all right, title, and interest in the '124 patent. A true and correct copy of the '124 patent is attached as Exhibit C to this Complaint.

16. On January 8, 2013, U.S. Patent No. 8,349,239 ("the '239 patent"), entitled "SEAM CONCEALMENT FOR THREE-DIMENSIONAL MODELS," was duly and lawfully issued by the United States Patent and Trademark Office. Stratasys was assigned

and continues to hold all right, title, and interest in the ’239 patent. A true and correct copy of the ’239 patent is attached as Exhibit D to this Complaint.

INFRINGING PRODUCT

17. On information and belief, Afinia makes, uses, offers to sell, and/or sells within the United States and/or imports into the United States an Afinia H-Series 3D Printer, an example of which is shown below.

(*See* Exhibit E, Afinia H-Series 3D Printer User’s Manual, cover.)

18. The Afinia H-Series 3D Printer creates 3D objects, which, for example, can be used for prototyping and design purposes. Generally speaking, the 3D model is created by delivering plastic filament from a spool through an extruder and nozzle, which heats the filament to printing temperature and deposits it onto a platform. The filament is deposited layer-by-layer in a pattern to create a 3D model. (*See, e.g.*, Exhibit E, Afinia H-Series 3D

Printer User's Manual at 6; *see also*, *e.g.*, Afinia Product Videos, available at http://www.afinia.com/support/product-videos (last visited Nov. 22, 2013); Afinia Video, available at http://www.youtube.com/watch?v=RoXLsHJwmnE (last visited Nov. 22, 2013).)

19. Afinia markets and sells the Afinia H-Series 3D Printer to the general public, including to hobbyists and educators and to persons interested in using the printer for prototyping and design purposes. (*See*, *e.g.*, Afinia Product Videos, available at http://www.afinia.com/support/product-videos (last visited Nov. 22, 2013); Afinia Video, available at http://www.youtube.com/watch?v=RoXLsHJwmnE (last visited Nov. 22, 2013).)

20. Afinia sells the Afinia H-Series 3D Printer at least through its website (https://store.afinia.com/) and online retailers. Afinia also distributes marketing, instructional, and support materials for the Afinia H-Series 3D Printer to customers through its website. (*See* Exhibit E, Afinia H-Series 3D Printer User's Manual; Exhibit F, Afinia H-Series Product Brochure; Afinia Product Videos, available at http://www.afinia.com/support/product-videos (last visited Nov. 22, 2013); Afinia Technical Videos, available at http://www.afinia.com/support/technical-videos (last visited Nov. 22, 2013).)

21. On information and belief, before and/or during development of the Afinia H-Series 3D Printer, Afinia investigated and analyzed the market and business opportunities for 3D printer technology. On information and belief, Afinia is believed to have obtained knowledge of patents of competitors, likely including patents of Stratasys, before and/or

during the research and development of the Afinia H-Series 3D Printer. (*See* Exhibit G, *Executive Interview: Mitch Ackmann*, 3D Printing Industry (Aug. 28, 2013) (President of Afinia).) Afinia is also believed to have obtained and analyzed 3D printers of its competitors, which likely would include Stratasys Inc. and MakerBot printers. (*Id.*)

COUNT 1
INFRINGEMENT OF THE ’925 PATENT

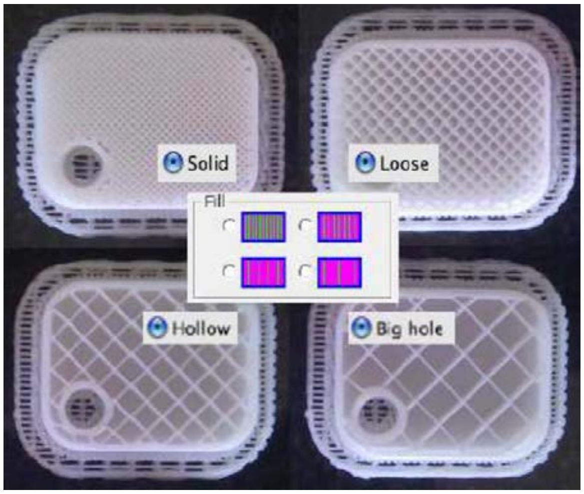
22. Stratasys reaffirms and realleges the allegations set forth in Paragraphs 1-21 above.

23. The ’925 patent generally relates to methods for controlling the porosity of objects through, among other things, adjusting the rate of deposition of material to create gaps as the object is built up layer by layer. (*See* Exhibit A.)

24. At least as of the date of filing of this Complaint, Afinia has knowledge of the ’925 patent.

25. On information and belief, the Afinia H-Series 3D Printer has been and/or is being used in a manner that infringes at least one claim of the ’925 patent.

26. The Afinia H-Series 3D Printer includes porosity controls. For example, the User’s Manual for the Afinia H-Series 3D Printer describes “Fill Settings” that allow the user to select from “four ways to fill the interior of the parts.” (Exhibit E, Afinia H-Series 3D Printer User’s Manual at 24.) These Fill Settings provide a pre-determined porosity for a 3D object by adjusting the rate of the dispensing material. Afinia includes the following graphic in its User’s Manual, showing how the porosity controls will vary the porosity of an object made with the Afinia H-Series 3D Printer:



(*Id*.)

27. On information and belief, Afinia has directly infringed and is directly infringing the ’925 patent under 35 U.S.C. § 271(a) by its use of the Afinia H-Series 3D Printer in the United States to perform at least one claim of the ’925 patent.

28. In addition, on information and belief, at least as of the filing date of this Complaint, Afinia has actively induced and is actively inducing others, such as Afinia’s customers, to directly infringe at least one claim of the ’925 patent in the United States, in violation of 35 U.S.C § 271(b). For example, on information and belief, Afinia has sold or otherwise provided its Afinia H-Series 3D Printer to third parties, such as Afinia’s customers, the use of which by Afinia’s customers has directly infringed and is directly infringing at least one claim of the ’925 patent. The Afinia H-Series 3D Printer, for example, includes the “Fill Settings” described above for controlling porosity in the 3D object. Afinia, moreover, specifically intends and encourages its customers to use its Afinia H-Series 3D Printer in violation of the ’925 patent. This is shown from Afinia’s User’s Manual for the Afinia H-Series 3D Printer, which describes the use of the “Fill

Settings," which in turn control the porosity of the 3D object created using the Afinia H-Series 3D Printer. Afinia, therefore, intends and encourages its customers to select a porosity when printing a 3D model with the Afinia H-Series 3D Printer and to therefore use the Afinia H-Series 3D Printer in violation of one or more claims of the '925 patent.

29. In addition, on information and belief, at least as of the filing date of this Complaint, Afinia has contributed to and is contributing to the direct infringement of at least one claim of the '925 patent by third parties, such as Afinia's customers, in the United States, in violation of 35 U.S.C § 271(c). For example, on information and belief, Afinia has contributed to and is contributing to infringement of the '925 patent by selling its customers Afinia H-Series 3D Printers, the use of which by Afinia's customers has directly infringed and is directly infringing at least one claim of the '925 patent. Indeed, on information and belief, each "Fill Setting" for the Afinia H-Series 3D Printer creates gaps between the material, and there does not appear to be a fill setting option other than those identified in the User's Manual. Accordingly, there are no substantial and non-infringing uses of the Afinia H-Series 3D Printer. The Afinia H-Series 3D Printer is also a material part of the invention of the '925 patent, as use of the device infringes one or more claims of the '925 patent.

30. On information and belief, Afinia will continue to directly infringe, actively induce others to infringe, and/or contribute to the infringement of the '925 patent unless and until Afinia is enjoined by this Court.

31. As a result, Stratasys will be damaged and will be irreparably injured unless and until Afinia's infringing activities are enjoined by this Court.

32. On information and belief, and as explained above, Afinia had knowledge of competitor patents before and/or during development of the Afinia H-Series 3D Printer. Afinia is also believed to have obtained and analyzed 3D printers of its competitors. If Stratasys learns of facts during discovery that show willful infringement of the ’925 patent, Stratasys reserves the right to and intends to assert willful infringement of the ’925 patent.

COUNT II
INFRINGEMENT OF THE ’058 PATENT

33. Stratasys reaffirms and realleges the allegations set forth in Paragraphs 1-32 above.

34. The ’058 patent generally relates to methods for controlling the solidification of extruded materials in layers by, among other things, maintaining a build environment in the vicinity where material is deposited at a temperature above a solidification temperature. The claimed methods tend to reduce the impact of curl deformation due to internal stresses created in the object during solidification. (*See* Exhibit B.)

35. At least as of the date of filing of this Complaint, Afinia has knowledge of the ’058 patent.

36. On information and belief, the Afinia H-Series 3D Printer has been and/or is being used in a manner that infringes at least one claim of the ’058 patent.

37. The Afinia H-Series 3D Printer maintains a heated build environment above the solidification temperature at least through the heating of the platform upon which the extruder deposits the material.

38. For example, the User's Manual for the Afinia H-Series 3D Printer emphasizes that "[o]ne of the keys to successful printing on the Afinia H-Series 3D Printer **is platform preparation** and **preheating**" and that a "**very well preheated**" platform will achieve the best results:

> ## Printing
>
> **TIP:** One of the keys to successful printing on the Afinia H-Series 3D Printer is **platform preparation** and **preheating**. Particularly with large parts, there is a tendency for the edges of the part to lift from the platform (which can be a little colder than the center) and cause the parts to warp. The best results will be achieved if:
>
> - The platform is perfectly level and calibrated
> - The nozzle height is correctly set
> - The printer is being run in a room that is not too cold (warmer than 65° F) and free of drafts
> - **The platform is very well preheated**

(Exhibit E, Afinia H-Series 3D Printer User's Manual at 26.) In fact, the Afinia H-Series 3D Printer includes a "Table Heat 1hr" option which heats the platform to 105°C for a full hour. (*Id*. at 17.)

39. In addition, the User's Manual explains that the extruder nozzle "heats the filament to printing temperature and deposits it on the Platform," and cautions the user that "[t]he extruder and platform are hot." (Exhibit E, Afinia H-Series 3D Printer User's Manual at 6, 31.)

40. The User's Manual for the Afinia H-Series 3D Printer further states that "Preheating the platform (see page 26) to at least 90 degrees C when printing with ABS is a step you don't want to miss." (Exhibit E, Afinia H-Series 3D Printer User's Manual at 34.) The manual also teaches to "[p]osition the parts as close to the center of the platform as possible," which is "where the heating is most regulated." (*Id*.)

41. On information and belief, Afinia has directly infringed and is directly infringing the ’058 patent under 35 U.S.C. § 271(a) by its use of the Afinia H-Series 3D Printer in the United States to perform at least one claim of the ’058 patent.

42. In addition, on information and belief, at least as of the date of filing of this Complaint, Afinia has actively induced and is actively inducing others, such as Afinia’s customers, to directly infringe at least one claim of the ’058 patent in the United States, in violation of 35 U.S.C § 271(b). For example, on information and belief, Afinia has sold or otherwise provided its Afinia H-Series 3D Printer to third parties, such as Afinia’s customers, the use of which by Afinia’s customers has directly infringed and is directly infringing at least one claim of the ’058 patent. The Afinia H-Series 3D Printer, on information and belief, includes a platform heating feature that will maintain a build environment in the vicinity where material is deposited at a temperature above a solidification temperature. Afinia, moreover, specifically intends and encourages its customers to use its Afinia H-Series 3D Printer and to, among other things, maintain a temperature above a solidification temperature in violation of the ’058 patent. This is shown from the User’s Manual for the Afinia H-Series 3D Printer, which, for example, instructs users to preheat the platform before depositing the material. As explained above, the User’s Manual emphasizes that the platform should be “very well preheated.” (Exhibit E, Afinia H-Series 3D Printer User’s Manual at 26.) The User’s Manual also states that “[t]he extruder and platform are hot,” (*id*. at 31), and that preheating the platform “is a step you don’t want to miss,” (*id*. at 34).

43. In addition, on information and belief, at least as of the date of filing of this Complaint, Afinia has contributed to and is contributing to direct infringement of at least one claim of the ’058 patent by third parties, such as Afinia’s customers, in the United States, in violation of 35 U.S.C § 271(c). For example, on information and belief, Afinia has contributed to and is contributing to infringement of the ’058 patent by selling its customers Afinia H-Series 3D Printers, the use of which by Afinia’s customers has directly infringed and is directly infringing the ’058 patent. Indeed, on information and belief, the Afinia H-Series 3D Printer does not have any substantial and non-infringing uses. The User’s Manual, for example, emphasizes that to avoid undesirable lift at the corners of an object, the platform should be preheated. (Exhibit E, Afinia H-Series 3D Printer User’s Manual at 34.) The User’s Manual also states that the platform should be “very well preheated,” (*id.*at 26), that “[t]he extruder and platform are hot,” (*id*. at 31), and that preheating the platform “is a step you don’t want to miss,” (*id.* at 34). The Afinia H-Series 3D Printer is also a material part of the invention of the ’058 patent, as use of the device infringes one or more claims of the ’058 patent.

44. On information and belief, Afinia will continue to directly infringe, actively induce others to infringe, and/or contribute to the infringement of the ’058 patent unless and until Afinia is enjoined by this Court.

45. As a result, Stratasys will be damaged and will be irreparably injured unless and until Afinia’s infringing activities are enjoined by this Court.

46. On information and belief, and as explained above, Afinia had knowledge of competitor patents before and/or during development of the Afinia H-Series 3D Printer.

Afinia is also believed to have obtained and analyzed 3D printers of its competitors. If Stratasys learns of facts during discovery that show willful infringement of the ’058 patent, Stratasys reserves the right to and intends to assert willful infringement of the ’058 patent.

COUNT III
INFRINGEMENT OF THE ’124 PATENT

47. Stratasys reaffirms and realleges the allegations set forth in Paragraphs 1-46 above.

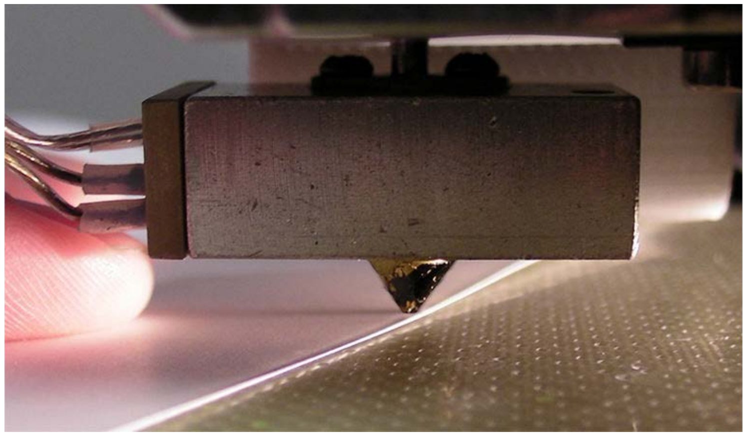
48. The ’124 patent generally relates to an apparatus for controlling the temperature of extrudable material in the liquifier of the extruder through the use of a novel thin-wall tube construction in the liquifier. (*See* Exhibit C.)

49. Stratasys makes and sells 3D printers that are embodied by one or more claims of the ’124 patent.

50. Stratasys has complied with 35 U.S.C. § 287(a) by marking its products with the ’124 patent.

51. On information and belief, Afinia has directly infringed and is directly infringing at least one claim of the ’124 patent under 35 U.S.C. § 271(a) by making, using, offering to sell, and/or selling within the United States and/or importing into the United States its Afinia H-Series 3D Printer and extruder replacement parts.

52. On information and belief, the Afinia H-Series 3D Printer includes a liquifier having a thin-wall tube with a section of the tube encased in a heating block. Depicted below is a photograph from the Afinia H-Series 3D Printer User’s Manual, which generally shows a portion of the extruder assembly, which includes a thin-wall tube liquifier:



(Exhibit E, Afinia H-Series 3D Printer User's Manual at 14.)

53. On information and belief, Afinia will continue to directly infringe the '124 patent unless and until Afinia is enjoined by this Court.

54. As a result, Stratasys will be damaged and will be irreparably injured unless and until Afinia's infringing activities are enjoined by this Court.

55. On information and belief, and as explained above, Afinia had knowledge of competitor patents before and/or during development of the Afinia H-Series 3D Printer. Afinia is also believed to have obtained and analyzed 3D printers of its competitors. If Stratasys learns of facts during discovery that show willful infringement of the '124 patent, Stratasys reserves the right to and intends to assert willful infringement of the '124 patent.

COUNT IV
INFRINGEMENT OF THE '239 PATENT

56. Stratasys reaffirms and realleges the allegations set forth in Paragraphs 1-55 above.

57. The '239 patent generally relates to methods for concealing layer seams by generating a contour tool path for a layer of extruded material, where the contour tool path

comprises a start point, a stop point, and a path between the start point and the stop point that seals a perimeter of a layer. For example, the start and/or stop points may be located within the interior of a perimeter of the contour tool path as, for example, illustrated in Figure 10 of the ’239 patent:

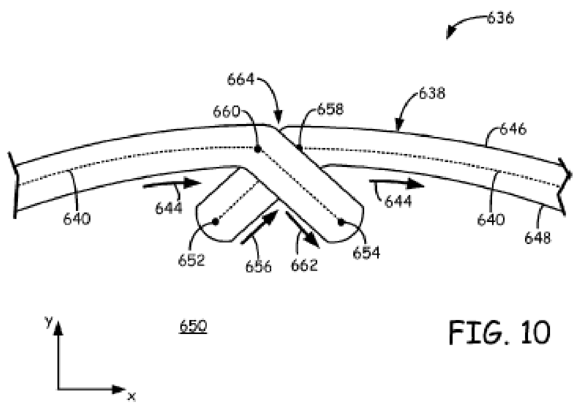


FIG. 10

(*See* Exhibit D.)

58. At least as of the date of filing of this Complaint, Afinia has knowledge of the ’239 patent.

59. On information and belief, the Afinia H-Series 3D Printer has been and/or is being used in a manner that infringes at least one claim of the ’239 patent.

60. On information and belief, the Afinia H-Series 3D Printer creates a contour tool path that generates seams that seal a perimeter of a layer. For example, the start and/or stop points of the contour tool path are at a location within the interior region of a perimeter of a layer.

61. On information and belief, Afinia has directly infringed and is directly infringing the ’239 patent under 35 U.S.C. § 271(a) by its use of the Afinia H-Series 3D Printer in the United States to perform at least one claim of the ’239 patent.

62. In addition, on information and belief, at least as of the filing date of this Complaint, Afinia has actively induced and is actively inducing others, such as Afinia's customers, to directly infringe at least one claim of the '239 patent in the United States, in violation of 35 U.S.C § 271(b). For example, on information and belief, Afinia has sold or otherwise provided its Afinia H-Series 3D Printer to third parties, such as Afinia's customers, the use of which by Afinia's customers has directly infringed and is directly infringing at least one claim of the '239 patent. Afinia, moreover, specifically intends and encourages its customers to use the Afinia H-Series 3D Printer along with custom designed software in violation of the '239 patent. Afinia, for example, includes "custom designed" Afinia software with the Afinia H-Series 3D Printer. (Exhibit E, Afinia H-Series 3D Printer User's Manual at 6; Afinia Product Videos, available at http://www.afinia.com/support/product-videos (last visited Nov. 22, 2013).) In addition, Afinia instructs users of the Afinia H-Series 3D Printer how to load and run the Afinia software. (*See* Exhibit E, Afinia H-Series 3D Printer User's Manual at 9 ("Driver and Software Installation"); Afinia Technical Videos, available at http://www.afinia.com/support/technical-videos (last visited Nov. 22, 2013).) Furthermore, Afinia states: "Our printer provides superior fit and finish so you know your prints will be strong and look great." (Afinia Product Videos, available at http://www.afinia.com/support/product-videos (last visited Nov. 22, 2013).) On information and belief, in order to provide "superior fit and finish," the Afinia H-Series 3D Printer, in conjunction with the software, creates a contour tool path that generates seams in violation of at least one claim of the '239 patent. Afinia therefore encourages and

intends for its customers to use the Afinia H-Series 3D Printer in a manner that violates one or more claims of the ’239 patent.

63. In addition, on information and belief, at least as of the filing date of this Complaint, Afinia has contributed to and is contributing to direct infringement of at least one claim of the ’239 patent by third parties, such as Afinia’s customers, in the United States, in violation of 35 U.S.C § 271(c). For example, on information and belief, Afinia has contributed to and is contributing to infringement of the ’239 patent by selling its customers Afinia H-Series 3D Printers, the use of which by Afinia’s customers has directly infringed and is directly infringing the ’239 patent. Indeed, on information and belief, the Afinia H-Series 3D Printer software is specifically designed to create a concealed seam by generating a contour tool path in violation of at least one claim of the ’239 patent. On information and belief, there are no substantial and non-infringing uses relating to the Afinia H-Series 3D Printer. For example, on information and belief, in order to provide “superior fit and finish,” the Afinia H-Series 3D Printer, in conjunction with the software, creates a contour tool path that generates seams in violation of at least one claim of the ’239 patent. The Afinia H-Series 3D Printer is also a material part of the invention of the ’239 patent, as use of the device infringes one or more claims of the ’239 patent.

64. On information and belief, Afinia will continue to directly infringe, actively induce others to infringe, and/or contribute to the infringement of the ’239 patent unless and until Afinia is enjoined by this Court.

65. As a result, Stratasys will be damaged and will be irreparably injured unless and until Afinia’s infringing activities are enjoined by this Court.

66. On information and belief, and as explained above, Afinia had knowledge of competitor patents before and/or during development of the Afinia H-Series 3D Printer. Afinia is also believed to have obtained and analyzed 3D printers of its competitors. If Stratasys learns of facts during discovery that show willful infringement of the ’239 patent, Stratasys reserves the right to and intends to assert willful infringement of the ’239 patent.

PRAYER FOR RELIEF

Wherefore, Stratasys requests entry of a judgment against Afinia granting the following relief:

A. Finding Afinia liable for infringement of the patents-in-suit;

B. Awarding Stratasys damages adequate to compensate for the infringement, including its lost profits and no less than a reasonable royalty;

C. Declaring this an exceptional case within the meaning of 35 U.S.C. § 285 and awarding Stratasys its reasonable attorneys’ fees, costs and disbursements;

D. Awarding Stratasys interest on all damages awarded;

E. Preliminarily and permanently enjoining Afinia, together with any officers, agents, servants, employees, and attorneys and such other persons in active concert or participation with them who receive actual notice of the order, from further infringement of the patents-in-suit; and

F. Awarding such other relief as is just and proper.

DEMAND FOR JURY TRIAL

Plaintiff Stratasys demands a trial by jury of all issues triable by a jury.

Dated: November 25, 2013

s/ Kenneth A. Liebman

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EXHIBIT A

US005653925A

United States Patent [19]

Batchelder

[11] **Patent Number:** **5,653,925**

[45] **Date of Patent:** **Aug. 5, 1997**

[54] **METHOD FOR CONTROLLED POROSITY THREE-DIMENSIONAL MODELING**

[75] Inventor: **John S. Batchelder**, Somers, N.Y.

[73] Assignee: **Stratasys, Inc.**, Eden Prairie, Minn.

[21] Appl. No.: **533,793**

[22] Filed: **Sep. 26, 1995**

[51] **Int. Cl.**[6] **B29C 41/02**

[52] **U.S. Cl.** **264/113**; 156/62.2; 264/308

[58] **Field of Search** 264/41, 113, 308, 264/401, 497; 156/62.2

[56] **References Cited**

U.S. PATENT DOCUMENTS

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5,518,680 5/1996 Cima et al. 264/401

Primary Examiner—Leo B. Tentoni
Attorney, Agent, or Firm—Moore & Hansen

[57] **ABSTRACT**

A method of making a three dimensional object by depositing material in a predetermined pattern on a receiving surface, and introducing a predetermined porosity into the object being formed by positioning the deposited material so as to introduce pockets of air or other fluid into the part, and by adjusting the rate at which the material is dispensed from the dispenser. Optimal porosities in the object to be built depend upon the shape of the material when it is dispensed, but range generally from 1% to 26%.

16 Claims, 3 Drawing Sheets

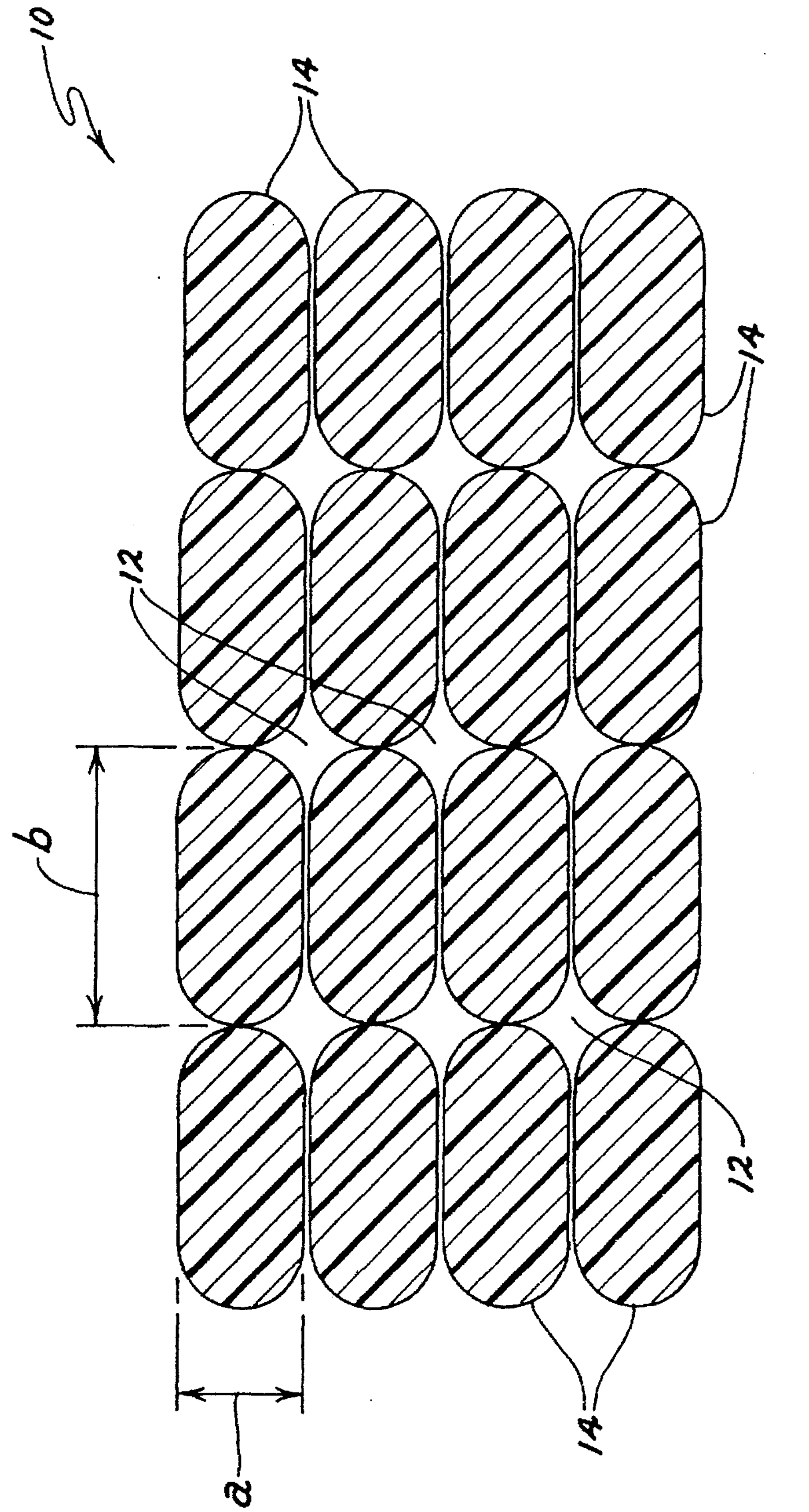

FIG. 1

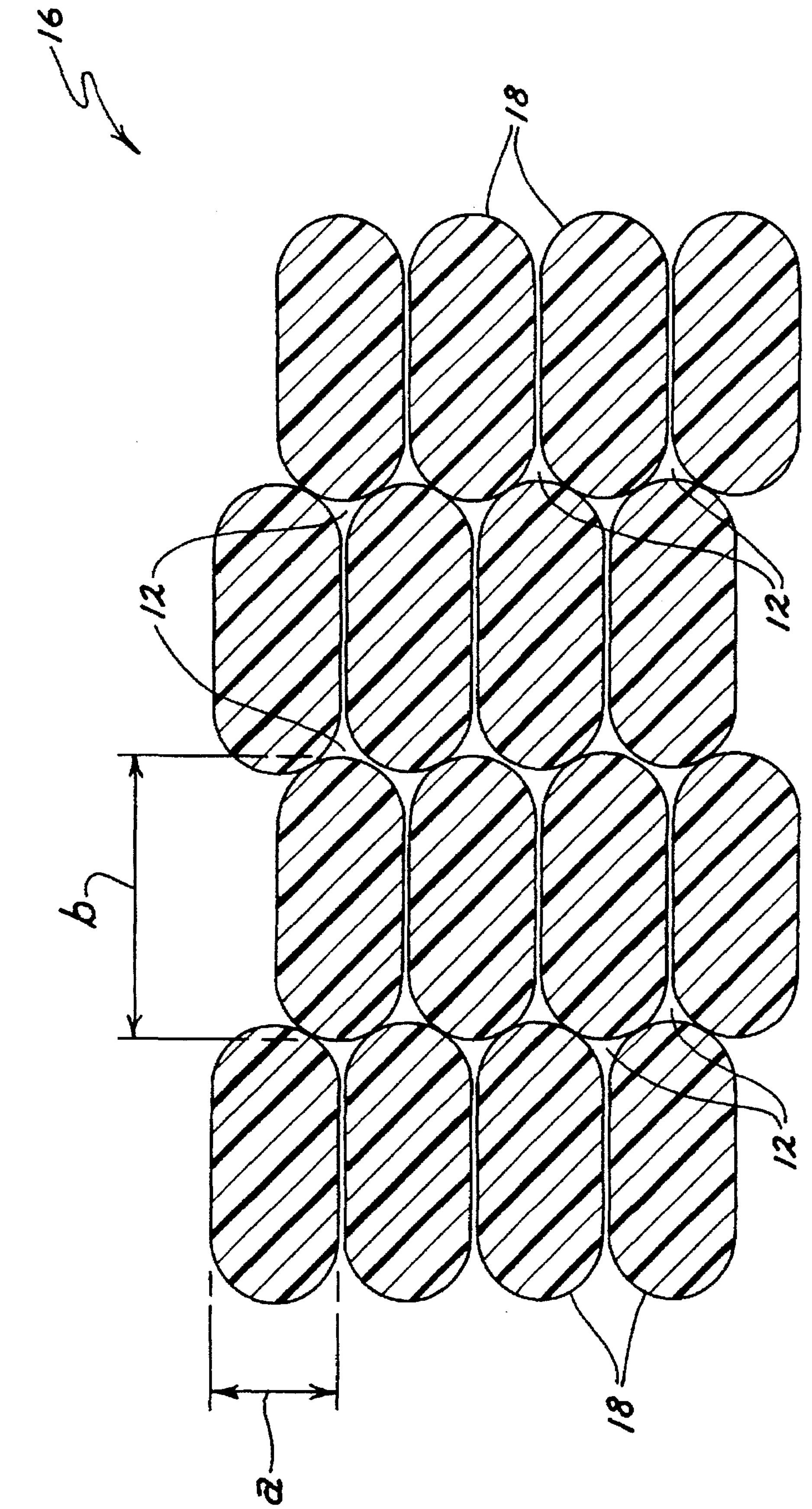

FIG. 2

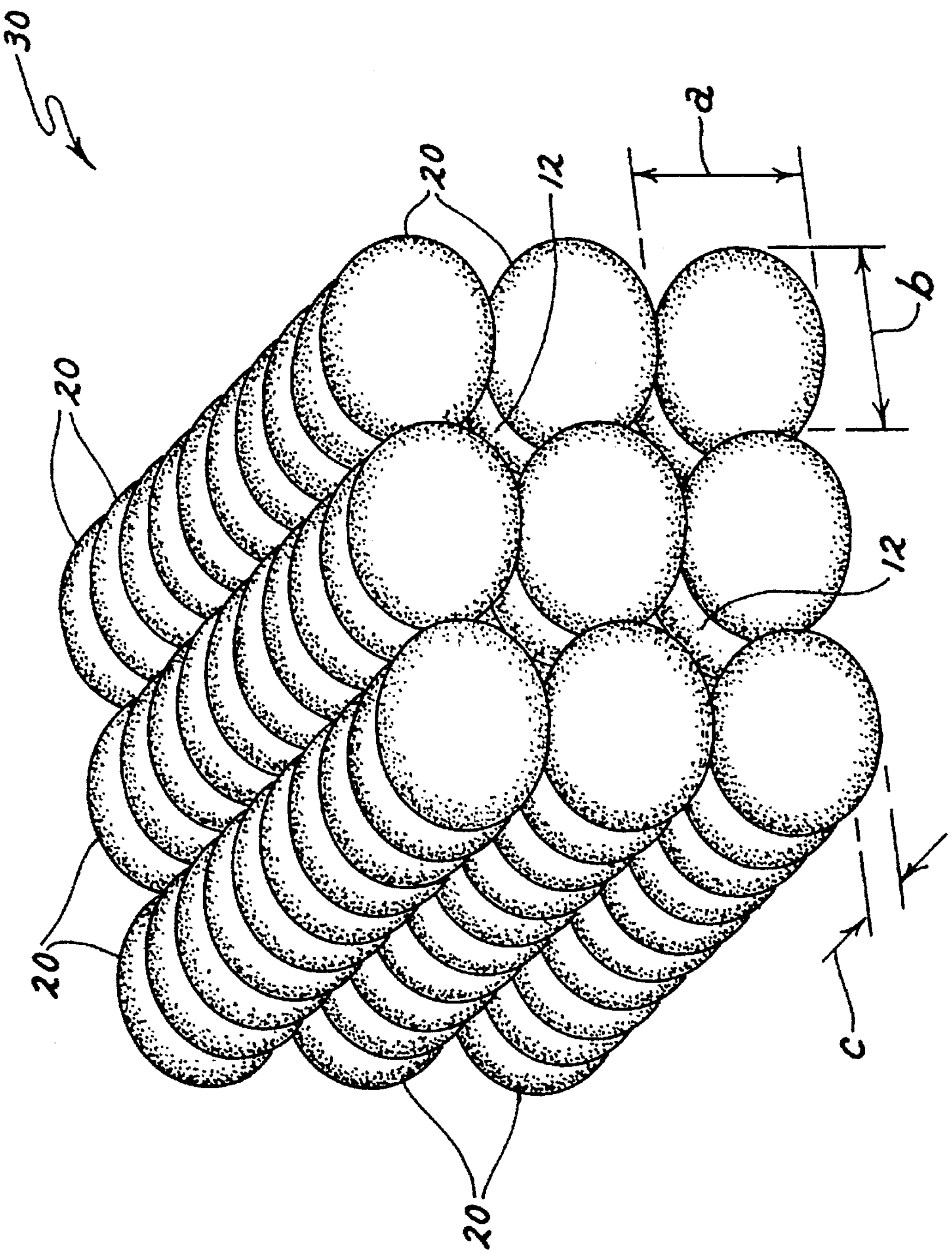

FIG. 3

METHOD FOR CONTROLLED POROSITY THREE-DIMENSIONAL MODELING

BACKGROUND OF THE INVENTION

The present invention relates to the field of three-dimensional prototype modeling. Specifically, it relates to a method of producing a prototype model having a set non-zero porosity determined by the type of packing pattern used to build the part.

To build an acceptable part, placement of sequentially applied material must currently be tightly controlled, because any errors in its placement will create dimensional errors that propagate throughout the part. Further, it is very difficult to accurately determine the impact of material placement errors at one layer on the accuracy of different layers of an article.

In ideal conditions for three-dimensional prototype modeling using continuous element deposition, if a deposition gun or extrusion head extrudes a bead of uniform area A at all extrusion speeds and if the bead trajectories are designed so that the beads have a horizontal spacing between them of "b" and a vertical spacing between them of "a," and A=ab, then a part having the proper dimensions will be produced. In discrete element deposition, if a deposition jet deposits droplets of volume V and the impact locations have a horizontal spacing between them of "b" and "c" and a vertical spacing of "a", then if V=abc, a part having the proper dimensions will be produced.

However, ideal conditions rarely exist, and numerous problems with accuracy of solid part dimensions are introduced into rapid prototyping processes. For example in continuous bead deposition, if a displacement pump is not used, the amount of material extruded per unit time depends non-linearly on the rate at which the pump is operated. In both continuous and discrete element deposition, in areas of high surface curvature physical characteristics of the material cause gaps between the beads; these physical characteristics include internal viscosity, surface tension, and rapid solidification.

In continuous bead extrusion rapid prototyping, there are two limiting cases for packing patterns for beads: rectangular and hexagonal. In a rectangular packing, the bead material must flow into 90 degree corners having infinitesimal radii to completely fill the volume. Problems occur in hexagonal packing, where the corners are 120 degrees. Beads are typically too viscous to fill in the 120 degree corners.

Another problem is that extrusion material varies from batch to batch. Further, material changes characteristics as it sits in a heated pot, because of absorption of and reaction with such things as water and oxygen from the air. All of the effects on the batches tend to cause the amount of material extruded in a bead or droplet at given pump speed to vary not only between batches, but also within batches.

Still another problem is that errors introduced into parts tend to propagate through the parts. Any error in a part, such as a lag or an excess of extrudate, will recur on all subsequent layers if the material is metered exactly. If a similar error occurs adjacent the first, the problem may even get worse in subsequent layers.

Extruded beads also change after extrusion. In continuous extrusion the material contracts as it cools; in addition beads contract axially and expand radially after being forced through the nozzle. For all of the above mentioned reasons, it is difficult to define exactly what the volumetric extrusion rate for a three-dimensional prototype modeling system is at any given time. It is also difficult to determine how one bead layer will lay on the next, due to the inherent uncertainty in the base layer.

There are several types of prototyping currently in use. Continuous extrusion based rapid prototyping involves depositing segments of continuous roads, ribbons, or beads of material onto a platform to sequentially build up an object. A cross section in a vertical plane of a number of such locally parallel beads normal to their axis will find that there are two limiting cases for how they can be packed together, namely in a rectangular array or in an hexagonal array. In the first case a longitudinal gap or pore tends to form along the line where four beads are nearest neighbors, and in the second case the pore forms along the line where three beads are nearest neighbors.

Lamination based rapid prototyping involves depositing shaped sheets or films to sequentially build up a solid object. Nominally these sheets join on continuous planes so that porosity is not necessarily present. Texturing the sheets with grooves or holes will introduce porosity that will help in lost wax casting applications, as described in the subsequent section. With this exception, parts manufactured with sheet laminations generally have zero porosity.

Discrete element extrusion based rapid prototyping involves depositing droplets or particles of material from a nozzle or projector so that the droplets sequentially build up a solid object. A cross section through such an object from any direction will show voids of some size at the locations where three, four, or even more droplets are nearest neighbors.

The techniques that we will subsequently describe for controlling rapid prototyping processes can be applied to several existing technologies. A brief review of these technologies shows that their practitioners have not realized the benefits of deliberately introducing porosity, especially at optimal levels.

For example, Batchelder et al. (U.S. Pat. No. 5,303,141) is silent on the role of part porosity. FIGS. **9***a*–**9***c* of Batchelder et al. depict beads deposited at the maximum possible porosity (cylindrical beads in line contact with their neighbors), which is not the preferred embodiment for practical part building.

Fujimaki et al. (Japan application 62-234910) shows a solid object being constructed from spherical particles in FIG. **4** and in the supporting text. Such a part has a greater porosity than is recommended. FIG. **4** shows a body centered cubic lattice of spheres creating the object, which would have a porosity of almost 45%. Each sphere would have only a point contact with its six nearest neighbors, which would create a weak part. FIGS. **6***a* and **6***b* show other part cross sections, where again the parts seem to be comprised of spheres in point contact.

Masters (U.S. Pat. No. 4,665,492) shows in FIGS. **2***a*–**2***c* that material deposited by ink jet like mechanisms will have some residual porosity, but is silent on the importance or optimization of that porosity.

The patents to Sachs et al. (U.S. Pat. Nos. 5,204,055 and 5,340,656) apply binder with an ink jet to a powder to make three dimensional parts. While there is an assumption that the powders are porous so that the binder fluid will wick into the powder, the patent is silent on any role or importance of porosity.

BRIEF SUMMARY OF THE INVENTION

It is an object of the present invention to provide a process for adjusting the deposition rate of three-dimensional modeling material to provide a finished article having a predetermined porosity greater than zero, in an optimal range for overall part strength, use of materials, improved post processing, and dimensional accuracy.

It is another object of the present invention to provide a process capable of building a model from material in the form of various elements including roads, beads, ribbons, droplets, particles, and sheets.

The present invention accomplishes these objectives by providing a method of making a three-dimensional article by dispensing a solidifiable material in a predetermined pattern, with elements of the material positioned to provide fluid pockets between the elements, and adjusting the rate of dispensing of the material to provide porosity within a predetermined range.

Rapidly prototyped parts are best formed in deposition based rapid prototyping systems when residual fluid pockets are dispersed throughout the part. These fluid pockets or voids should be contained in the nominally solid portions of the parts. While such parts are less strong and dense than non-porous parts, they are more dimensionally accurate, they allow parts to be built with a wider range of materials, they are less prone to breaking ceramic molds during lost wax casting, they can be created more repeatedly, and they can in some cases allow co-machining steps to be eliminated.

When building up a three dimensional solid article from a computer aided design (CAD) file by adding material in discrete or continuous extrusions, there are advantages in deliberately and systematically applying less material than would completely fill the interior of the part as defined by the CAD file. It is not necessary to completely fill solid all regions of the part. Fluid pockets between the extruded beads form an adjustable buffer.

The present invention provides a method to correctly and efficiently account for variations in the extrusion rate and element positioning that would otherwise lead to unacceptable parts. It does so by introducing a porosity into the part during manufacture. This porosity should be confuted within a range to allow reliable part strength. The introduction of porosity into parts allows the creation of a part that is insensitive to the small changes present in extrusion rates between and within batches. It further allows higher viscosity and surface tension in the extrudate, and provides an expansion cushion within the part to help prevent mold breakage during lost wax casting. Also, additional process steps such as co-machining may be eliminated.

These and other objects and benefits of the present invention will become apparent from the following detailed description thereof taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a vertical section view of a rectangular array of beads; and

FIG. **2** is a vertical section view of an hexagonal array of beads; and

FIG. **3** is an isometric view of a rectangular array of droplets.

DESCRIPTION OF THE PREFERRED EMBODIMENT

A computer aided design (CAD) file prescribing a three dimensional solid object such as objects **10**, **16**, and **30** typically contains surfaces bounding solid portions of the object. If a rapid prototyping system uses some building material with a density ρ to build that object so that only that building material exists within the corresponding surfaces of the prototype, then the resulting part has a density of ρ and it has a porosity of zero. Note that all of the solid regions of the part are 100 percent building material. If all of the solid regions of the part have systematic pores **12** that contain some other material, such as the fluid that fills the build volume prior to building the object (say that fluid has a density ρ_{air}, since air is the most common fluid used in application), then the resulting part might have a density of ρ_{part} and a porosity (P) of:

$$P = \frac{\rho - \rho_{part}}{\rho - \rho_{air}} \qquad \text{[Eq. 1]}$$

The pores such as pores **12** might be filled with a variety of fluids such as nitrogen, argon, water, oil, UV curable monomer, vacuum, water, glycol or liquid metal. The following description of porosity control will refer to air as the trapped fluid, since that will be the conditions normally encountered in actual practice, however other fluids are practical. Since air has roughly one thousandth the density of typical build materials the porosity simplifies to:

$$P = 1 - \frac{\rho_{part}}{\rho} \qquad \text{[Eq. 2]}$$

The examples that follow primarily consider the building of objects from elements of the same size and shape, such as beads of constant cross section and droplets of constant volume. Mixing elements of different sizes would allow the porosity to span larger ranges.

Consider three examples. In the first example, a part is built with an extrusion based rapid prototyping system depositing beads that are 5% smaller in cross sectional area than what would be required to deposit sufficient material to completely fill the part as specified in the associated CAD file. If the bead diameter required to completely fill the part is 0.015 inches, the actual bead average diameter would be 0.0146 inches. This smaller bead diameter would produce an exterior surface on the part that is displaced into the part on the order of 0.0005 inches. Other than this displacement, the part will be built successfully with a slight mount of air between the beads. Such a part will have a porosity greater than zero due to air gaps between the beads.

In the second example, the same part is built with the extrusion system with a bead cross sectional area size that is 20% smaller than nominal. In this situation there will be some regions of the part where the gaps between the beads are so great that nearest neighbor beads do not touch. Generally, parts manufactured with this bead size will delaminate and functionally fail due to excessive porosity.

In the third example, the same part is built with the extrusion system with a bead cross section area that is 5% larger than that which would entirely fill the part. At each layer of the part, material will be deposited in excess of the volume of the layer. This will typically manifest itself by the height of the part rising faster than the height of the extrusion nozzle. The nozzle will gradually dig further and further into the part, and will eventually knock over features or otherwise cause the part to fail.

The point of the examples is that variations in the amount of material being deposited are practically not detectable as long as the deposition rate is within a narrow range or window. When the rate that material is being applied goes outside of that narrow range, the error is not only un-forgiven, it is integrated.

Referring to FIG. **1**, for such a rectangular array **10** of beads or ribbons **14**, wherein "a" is the bead height and "b" is the bead width, the maximum porosity P_{max} may be calculated according to the equation:

$$Pmax_{rect\text{-}1D}=a/b(1-\pi/4)\cong a/b0.2146\leqq 0.2146 \qquad \text{[Eq. 3]}$$

wherein:

$$a\leqq b$$

Referring now to FIG. **2**, for such an hexagonal array **16** of beads or ribbons **18**, where "a" is the bead height and "b" is the bead width, and those dimensions are different, the maximum porosity may be calculated according to the equation:

$$Pmax_{hex\text{-}1D}=\frac{a}{2b}\left(\sqrt{3}-\frac{\pi}{2}\right)\cong\frac{a}{b}\ 0.0806\leqq 0.0931 \qquad \text{[Eq. 4]}$$

wherein:

$$a\leqq\frac{2b}{\sqrt{3}}$$

The highest porosity condition of approximately 21% exists when the beads are cylindrical in shape, arranged in a square array, and touch at most their four nearest neighbors. This will generally be the case for very stiff or rapidly solidifying materials applied in layers or strata of beads. Under these conditions, the cylindrical shaped beads as extruded will resist deforming into intimate contact with their nearest neighbors. In some cases the beads in adjacent horizontal layers will locally be parallel and laterally offset from each other by half a diameter. In this situation even stiff or rapidly solidifying materials will pack with a porosity of about 9%. Further, bead elements may be deposited in successive horizontal layers in a skew arrangement **50** as to provide a minimum porosity.

Some deformation of cylindrical beads is desirable for overall part strength and internal adhesion. Because it is possible for even rigid cylinders to configure themselves with a 9% porosity, and because most extrusion materials are sufficiently viscous that beads cannot be made to conform so as to make a porosity of less than 1%, an optimal condition for extrusion based porosity is 5%. This gives a process window of plus or minus 4%. If the material is being extruded such that the bead height "a" and width "b" are different and "a" is less than "b", the optimal porosity process window becomes:

$$P\ extrusion_{optimal}=a/b(0.05\pm 0.04) \qquad \text{[Eq. 5]}$$

The tolerance on the dimensions of the extruded bead is roughly half of the porosity tolerance, or 0.02a/b. The optimal porosity range for bead elements extruded in this manner is approximately 2–10%, with an optimal porosity of approximately 5%. Elliptical bead elements may also be used in this form of prototyping.

Beads which are significantly flattened are more difficult to produce because they require greater extrusion accuracy. For example, a road that is four times wider than it is high must be extruded with a volumetric or cross sectional accuracy of plus or minus 1%.

The foregoing discussion gives maximum porosities for bead extrusion rapid prototyping where adjoining beads have line contact, that is where the nearest neighbor beads have parallel axes. Considerably larger porosities are possible if beads are spaced sufficiently far apart within a layer

that they do not contact their nearest neighbors. This is possible only if the beads in one layer are not locally parallel to the beads in either adjoining layer. For example, this could be the case if the bead axes are oriented in a system such as a rectangular X-Y system along X in layer **1**, Y in layer **2**, X in layer **3**, and so forth. Under these conditions the process limits previously described give only a maximum lower bound to the porosity.

Ink jet or ballistic particle based rapid prototyping involves depositing droplets or particles of material so as to sequentially build up an object. This is typically implemented in a raster deposition pattern where an array of nozzles deposit droplets **20** of either final part material or support material on every location in a finely spaced rectilinear grid as shown in FIG. **3**. Assuming that the height of each such layer is "a", and that the length and width of each grid element are "b" and "c," respectively, the maximum porosity becomes:

$$Pmax_{ortho\text{-}3D}=a/bc((1-\pi/4)(b+c)-a(1-\pi/3)<0.4765 \qquad \text{[Eq. 6]}$$

The highest porosity is achieved for the case where a=b=c. Two other cases of interest are the face centered and body centered cubic lattices. Their maximum porosities are:

$$Pmax_{body}=1-\frac{\sqrt{3}\ \pi}{8}\cong 0.3198 \qquad \text{[Eq. 7]}$$

$$Pmax_{face}=1-\frac{\sqrt{2}\ \pi}{6}\cong 0.2595 \qquad \text{[Eq. 8]}$$

The closest packing of rigid spheres yields a porosity of about 26%. Since it is difficult to deposit materials even under optimal conditions with porosities of less than 1–2%, this defines the porosity process window for droplet deposition to be 14% plus or minus 12%. If the average height "a" of an impacted droplet is less than its lateral dimension "b", the optimal porosity process window becomes:

$$Pdroplet_{optimal}=a^2/b^2(0.14\pm 0.12) \qquad \text{[Eq. 9]}$$

Equation 9 points out the desirability of printing with nearly round droplets. For example, a typical wax jet printer produces solidified droplets that are about three times wider than they are high. The porosity process window for this type of printing would be 1.6% plus or minus 1.4%. If the volume of the individual droplets cannot reliably be held within a diameter tolerance of plus or minus 1.4%, there will be insufficient space between some of the solidified droplets to take up their volumetric variation, causing the part to build up unevenly. Post deposition machining may be required for flattened droplets while it may be avoidable for nearly symmetric droplets. The tolerance on the dimensions of the extruded droplet is roughly a third of the porosity tolerance, or $0.04(a/b)^2$. For rapid prototyping using elements extruded in this manner, the optimal porosity range is approximately 2–26%, with an optimal porosity of 14%.

Nearly symmetric droplets have an additional advantage in this type of prototyping in that the angle of incidence of the droplet can be altered without substantially changing the shape of the solidified droplet. This is important in deposition systems where the droplet nozzles have orientational degrees of freedom.

Objects are also printed by applying droplets of binder to a powder layer to selectively bond particles together and to the previously constructed object, or by selectively sintering particles. The porosity of these parts is difficult to prescribe, since it is a function of the particle size distribution, the degree of settling, the shapes of the particles, and (in the case of sintering) the amount of fusion of the particles. Residual porosity is desirable for these parts primarily for casting operations, to be described.

The Need for Finite Process Windows

Rapid prototyping systems attempt to miniaturize the entire manufacturing process into a single small space. Desktop rapid prototyping additionally requires that all of the supporting manufacturing engineering expertise usually required to keep a manufacturing process tuned to specified tolerances must be subsumed in the desktop system, so that a casual user can reliably and repeatedly create arbitrary geometries. There are at least four generic ways to make a reliable manufacturing process:

- Design an end product that is easy to manufacture. This avenue is generally unavailable in rapid prototyping. The designs of interest are usually printed with a rapid prototyping system exactly because they are difficult to manufacture.
- Tightly control all input parameters. This avenue is generally unavailable to desktop rapid prototyping. Ambient air temperature and humidity can vary, the age and condition of the material to be deposited is often not controlled, and there are numerous internal processes in the device such as bearing wear that gradually achieve somewhat unknown states.
- Apply active feedback. See for example U.S. Pat. No. 5,303,141.
- Use a process with a wide tolerance. If the intrinsic process is insensitive to variations of its input parameters within a defined window, the process can be robust.

Different rapid prototyping techniques have different failure modes that drive the need for a wide process window. Extrusion based rapid prototyping will typically evidence one of the following:

- Gas pockets form in the pressurized region of the delivery channel that change size as the pressures are changed. This leads to an unpredictability of the amount of material that will be extruded at a given instant.
- If a viscosity pump is used, the amount of material extruded per unit time depends non-linearly on the rate that the pump is being operated. If a gear pump or other quasi-continuous displacement pump is used, there are pulsations or variations in flow rate that also affect the instantaneous deposition rate.
- Deposition materials are typically chosen for good self-adhesion, stiffness, and rapid solidification. These same properties can cause the materials to resist filling in crevasses where the radius of the meniscus of the deposited material is small and positive.
- Material and pump characteristics change over time. These changes can be due to bearing wear, water absorption, temperature drift, oxidation, and batch to batch material variations.
- Errors tend to propagate through a part. Air may blow a bead to an adjacent position, or material may pull away from a corner instead of attaching, or a gas pocket may cause a momentary drop out of the bead. If the material is metered exactly and there is no tolerance for errors, the resulting defect will occur on all subsequent layers of the part, and possibly become worse on subsequent layers.

Porosity to Aid Lost Wax Casting

Lost wax casting allows replicas of a meltable part to be formed with high temperature castable materials. Typically

the original part is formed from a wax material. Sprues and vents are added of the wax material to allow the final material to enter and the wax to exit. The part is then coated with several layers of ceramic slurry which is cured to form a hard ceramic shell. The wax part with its shell is put in an oven to melt out most of the wax, and then the final material (such as steel) is poured in to create the part and burn out the residual wax.

Waxes for lost wax casting are specifically formulated to minimally expand prior to softening. Most materials for rapid prototyping expand significantly under the same conditions, primarily due to additional requirements from the rapid prototyping process. Since both the ceramic shell and the material filler are nearly incompressible, differences in their thermal expansion coefficients can generate enough force to crack the ceramic shells.

If non-zero porosity such as by air inclusions is introduced into the prototype part, the porosity will increase the part's compressibility and compensate for differences in thermal expansion coefficients. Assuming that gas trapped in the part pores behaves as an ideal gas, we can calculate the porosity required to keep the pressure from the part from rapturing the shell.

If the thermal expansion coefficient of the bulk prototype part material is $\eta_{material}$, the thermal expansion coefficient of the cured ceramic shell is η_{shell}, the ambient temperature is $T_{ambient}$, the temperature change required to make the material flow out of the shell is ΔT, the ambient pressure is $Press_{ambient}$, and the maximum pressure that the shell can tolerate from expansion of the material during the heating cycle is $Press_{hot}$, the minimum required porosity is:

$$Pmin = \left(1 + \frac{\eta_{shell}}{\eta_{material}} + \frac{1 - \left(1 + \frac{\Delta T}{T_{ambient}} \right) \frac{Press_{ambient}}{Press_{hot}}}{3\eta_{material}\Delta T} \right)^{-1} \quad \text{[Eq. 10]}$$

Under most circumstances this can be approximated by:

$$Pmin = \frac{3\eta_{material}\Delta T}{1 - \left(1 + \frac{\Delta T}{T_{ambient}} \right) \frac{Press_{ambient}}{Press_{hot}}} \quad \text{[Eq. 11]}$$

For example, a typical material might have an expansion coefficient of 25 parts per million per degree centigrade, be required to be heated by 150 degrees centigrade above STP to flow out of the mold, and the mold should be able to support one atmosphere of differential pressure from the hot material ($Press_{hot}$=2$Press_{ambient}$). In this case the minimum required porosity is 4.6%. The porosity requirements for lost wax casting are also compatible with those for reliable part building.

This analysis is independent of the nature of the part porosity as long as it is uniformly distributed through the part and the pores are filled with a gas. It suggests that lost wax casting is possible for materials other than the traditional casting waxes if sufficient porosity has been created in the master part.

A three-dimensional article may therefore be formed by depositing solidifiable material in such a manner as to control the porosity of the resulting part as follows. The dispenser moves in a predetermined pattern, extruding material in a predetermined size and shape. Such dispensing is controlled so as to sequentially deposit elements of material to form a part. The shape of the elements of material and the motion of the dispenser serves to create a part with a porosity content determined by the relationship between extrusion rate and element size and shape. The rate of dispensing the material may be adjusted to provide a range of porosities suitable for the formation of parts of varying characteristics.

Having thus shown the advantages of a deliberate introduction of porosity into rapid prototyping techniques, a method for building parts of predetermined porosity will now be disclosed. When it is desired to make a part of determined porosity, the rate of dispensing elements of material is varied so that the resulting product is of the desired porosity. The material is laid down sequentially by a dispenser onto a receiving surface in a pattern defined by the user. The material elements are deposited in a set position to provide air or other fluid pockets between them. The material dispensation rate may also be adjusted to assist in the formation of a part of predetermined porosity.

The dispenser may be any type of known dispenser used in the rapid prototyping industry, such as a nozzle using a pressurized supply source of material, providing a fluid material source. The pressurized material may be supplied by a positive displacement pump. This dispenser works best for providing bead elements that are elliptical in cross sectional shape. Another type of dispenser that may be used is an ink jet type dispenser that dispenses nearly spherical droplets.

As shown in the figures, bead elements may be deposited in successive horizontal layers so that the beads are in such horizontal and vertical juxtaposition as to be arranged in a rectangular or an hexagonal array. It is understood that beads may be deposited in a large variety of patterns not shown here.

The detailed description outlined above is considered to be illustrative only of the principles of the invention. Numerous changes and modifications will occur to those skilled in the art, and there is no intention to restrict the scope of the invention to the detailed description. The preferred embodiment having been described in detail, the scope if the invention will be defined by the following claims.

What is claimed is:

1. A method of making a three-dimensional article by the deposition of solidifiable material onto a receiving surface, with the article having a predetermined porosity comprising that fractional portion of the article that is devoid of such material, comprising the steps of:

dispensing solidifiable material onto a receiving surface from a dispenser moved in a predetermined pattern to create a three-dimensional article of predetermined size and shape, with dispensing of the material being controlled to sequentially build up the material to form the desired article;

depositing the material in multiple, adjacent elements, with the elements positioned to provide fluid pockets therebetween; and

adjusting the rate of dispensing of the material to provide a predetermined porosity in the article thus formed.

2. The method of claim 1 wherein said provided fluid pockets are air filled.

3. The method of claim 1 wherein:

the dispenser is a nozzle, and the material is supplied to the nozzle in a fluid state from a pressurizing supply source;

and extruding the material from the nozzle in the form of continuous beads defining said elements.

4. The method of claim 3 wherein:

the beads are generally elliptical in cross section.

5. The method of claim 3, wherein:

the pressurizing supply source is adjusted to provide a porosity in the article of between 1% and 9%, so as to form an article of a strength sufficient to maintain the integrity of the article.

6. The method of claim 5 wherein:

the pressurizing supply source is adjusted to provide a porosity in the article of approximately 5%.

7. The method of claim 1 wherein:

the dispenser is a droplet dispenser of the ink jet type; and

depositing the material in the form of droplets defining said elements.

8. The method of claim 7 wherein:

the droplet dispensing is controlled to provide a porosity in the article of between 2% and 26%.

9. The method of claim 8 wherein:

the droplet dispensing is controlled to provide a porosity in the article of approximately 14%.

10. The method of claim 7 wherein:

the droplets as deposited are substantially spherical in shape.

11. The method of claim 3 and comprising:

supplying the material to the nozzle from a positive displacement pump comprising the pressurizing supply source.

12. The method of claim 3 and comprising:

depositing said bead elements in successive horizontal layers with the beads in such juxtaposition to each other vertically and horizontally as to form a substantially rectangular array in vertical cross section.

13. The method of claim 3 and comprising:

depositing said bead elements in successive horizontal layers with the beads in such juxtaposition to each other vertically and horizontally as to form a substantially hexagonal array.

14. The method of claim 3 and further comprising the step of:

depositing said bead elements in successive horizontal layers, wherein said bead elements are skew to create a predetermined minimum porosity.

15. The method of claim 14 wherein said predetermined minimum porosity is approximately 1%.

16. The method of claim 1 wherein:

the rate of dispensing is adjusted to provide a porosity of between 1% and 21%.

* * * * *

EXHIBIT B

US005866058A

United States Patent [19]

Batchelder et al.

[11] **Patent Number: 5,866,058**

[45] **Date of Patent: Feb. 2, 1999**

[54] **METHOD FOR RAPID PROTOTYPING OF SOLID MODELS**

[75] Inventors: **John Samuel Batchelder**, Somers, N.Y.; **Steven Scott Crump**, Wayzata, Minn.

[73] Assignee: **Stratasys Inc.**, Eden Prairie, Minn.

[21] Appl. No.: **862,933**

[22] Filed: **May 29, 1997**

[51] **Int. Cl.**[6] **B29C 41/02**

[52] **U.S. Cl.** **264/237**; 264/308; 364/468.26

[58] **Field of Search** 264/237, 308, 264/401, 497; 364/468.26

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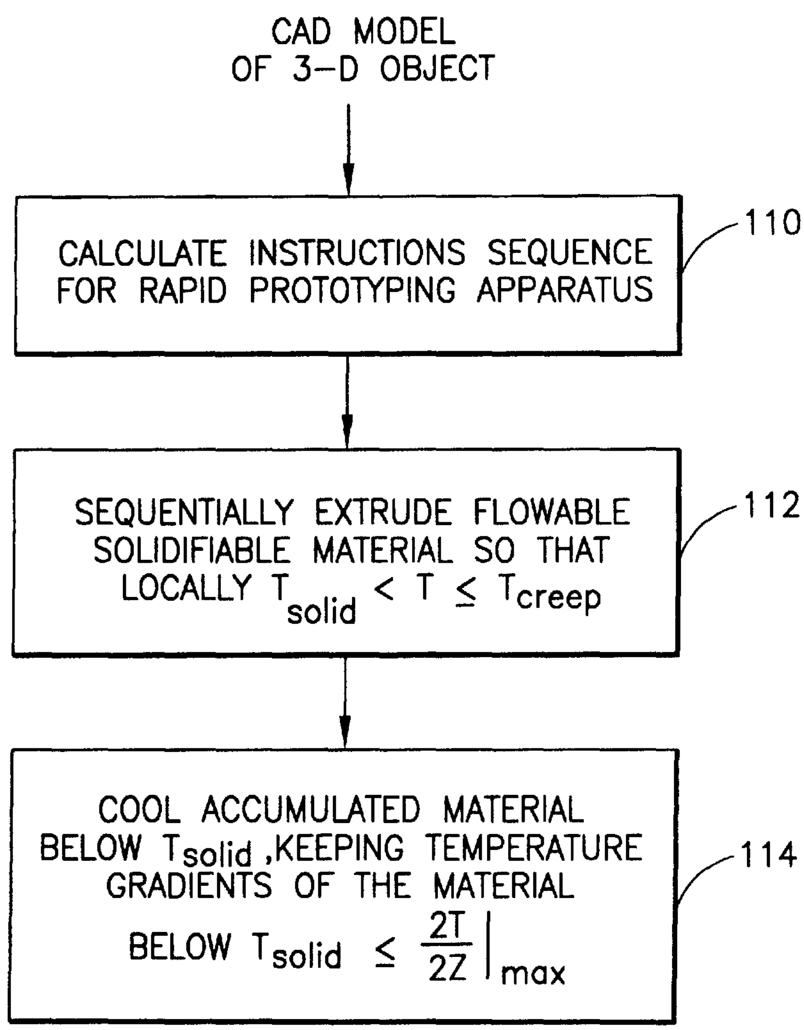
Primary Examiner—Leo B. Tentoni

Attorney, Agent, or Firm—Ohlandt, Greeley, Ruggiero & Perle

[57] **ABSTRACT**

Data corresponding to a desired shape of a prototype is transmitted to a rapid prototyping system. The system calculates a sequence for extruding flowable material that thermally solidifies so as to create the desired geometric shape. A heated flowable modeling material is then sequentially extruded at its deposition temperature into a build environment that maintains the volume in the vicinity of the newly deposited material in a deposition temperature window between the material's solidification temperature and its creep temperature. Subsequently the newly extruded material is gradually cooled below its solidification temperature, while maintaining temperature gradients in the geometric shape below a maximum value set by the desired part's geometric accuracy.

11 Claims, 3 Drawing Sheets



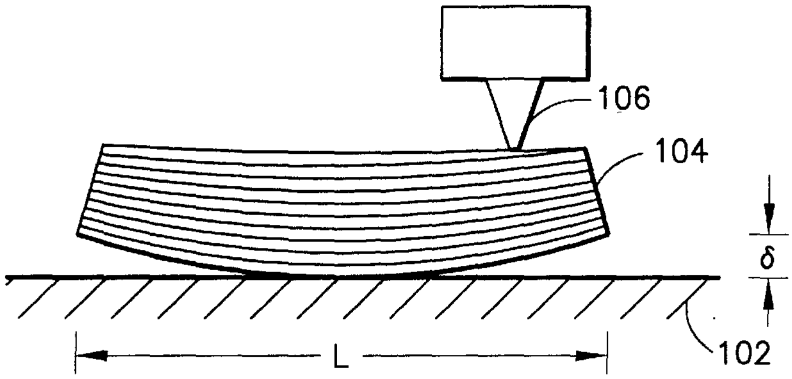


FIG. 1
PRIOR ART

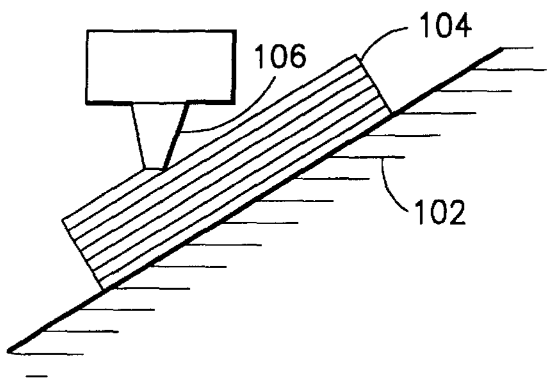


FIG. 2A
PRIOR ART

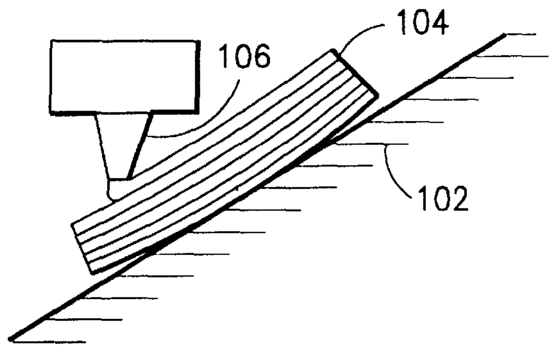


FIG. 2B
PRIOR ART

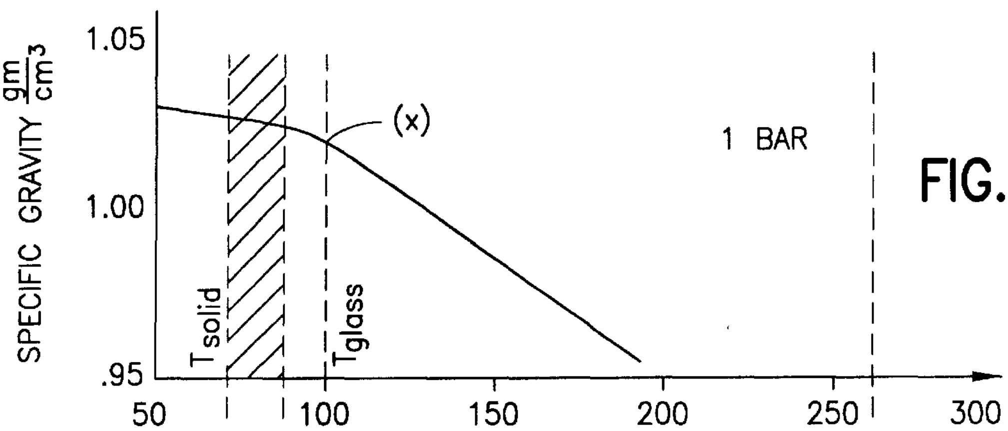


FIG.3A

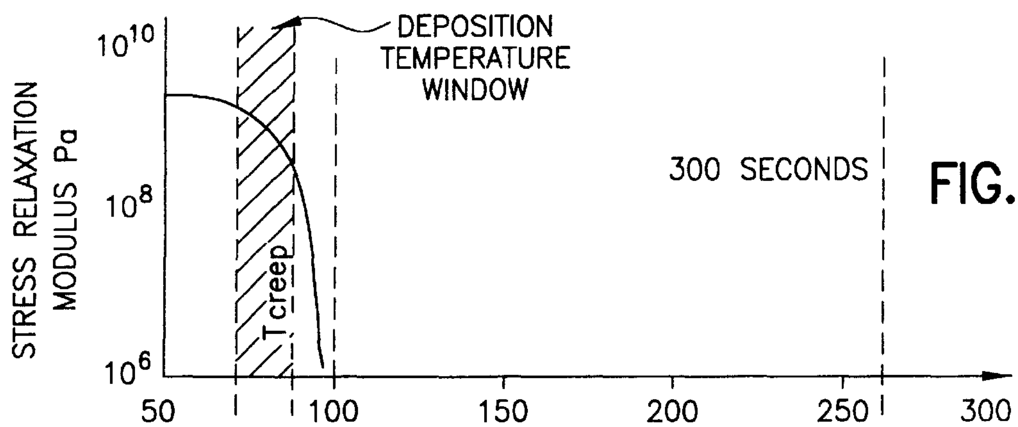


FIG.3B

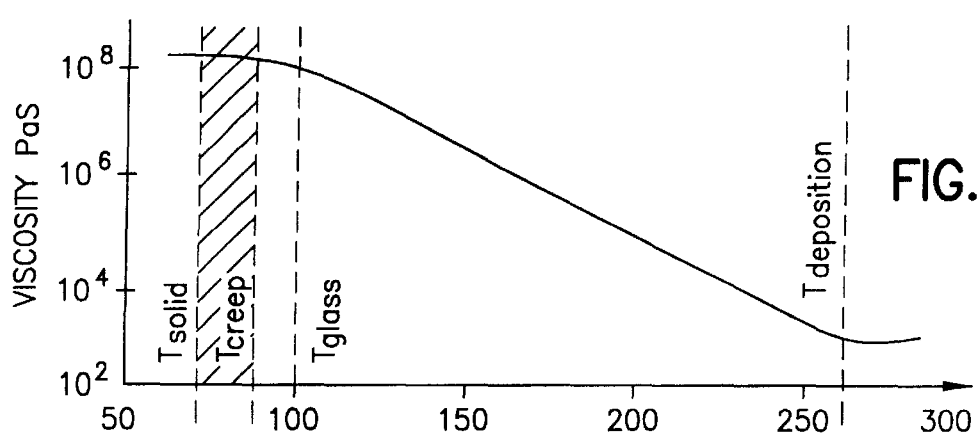


FIG.3C

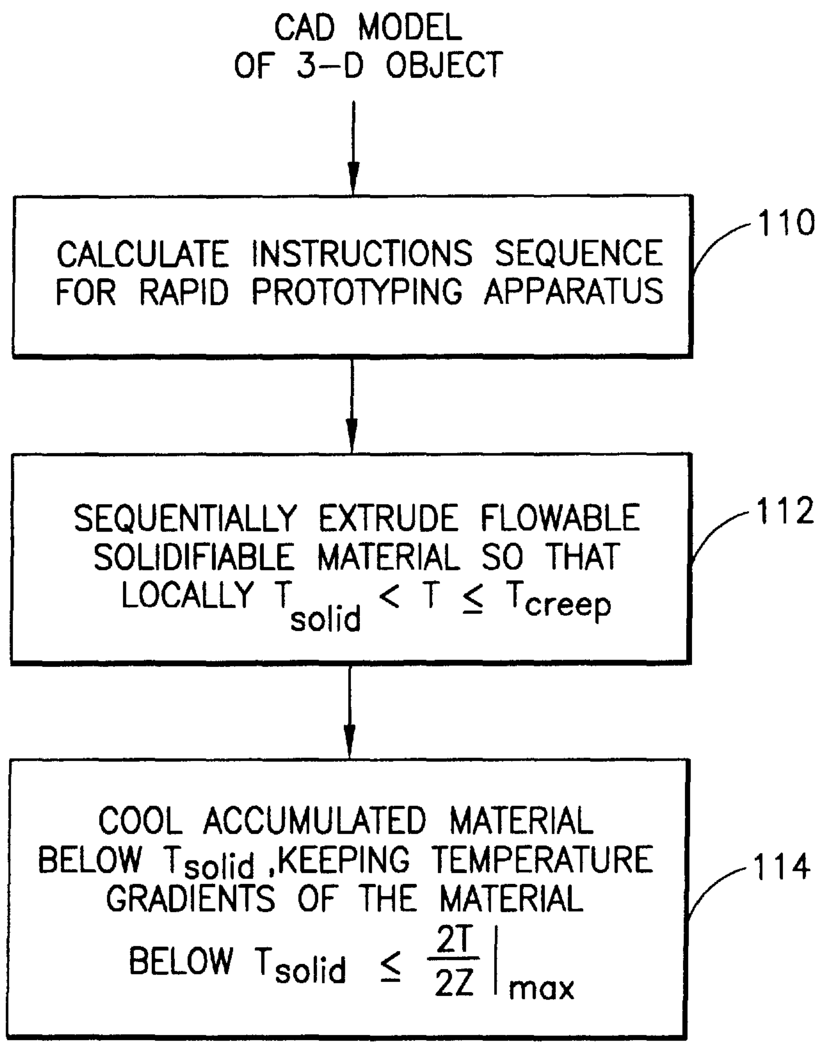

CAD MODEL
OF 3-D OBJECT
CALCULATE INSTRUCTIONS SEQUENCE
FOR RAPID PROTOTYPING APPARATUS
110
SEQUENTIALLY EXTRUDE FLOWABLE
SOLIDIFIABLE MATERIAL SO THAT
LOCALLY $T_{solid} < T \leq T_{creep}$
112
COOL ACCUMULATED MATERIAL
BELOW T_{solid}, KEEPING TEMPERATURE
GRADIENTS OF THE MATERIAL
BELOW $T_{solid} \leq \left.\frac{2T}{2Z}\right|_{max}$
114

FIG.4

METHOD FOR RAPID PROTOTYPING OF SOLID MODELS

FIELD OF THE INVENTION

This invention relates to the rapid prototyping of solid models from thermoplastic materials and, more particularly, to a method for rapid prototyping of models wherein curl and other modes of distortion are minimized.

BACKGROUND OF THE INVENTION

Rapid prototyping of models includes the making of three dimensional solid objects in accordance with a specified design, with the design usually comprising mathematical data from a three dimensional solid computer-aided design system. Rapid prototyping systems create solid objects by:

- sequential photopolymerization of layers of a monomer,
- milling away material,
- laser fusing of particulate,
- sequential extrusion of a thermoplastic,
- laminating scribed layers of paper,
- jetting thermally solidifiable wax or metal,
- laser enhanced chemical vapor deposition,
- brazing together pre-machined plates,
- by jetting binder onto ceramic powders,
- other techniques.

A preferred rapid prototyping system creates solid models by depositing thermally solidifiable materials. In these processes, a flowable material is sequentially deposited on a seed, a substrate, or on previously deposited thermoplastic material. The material solidifies after it is deposited and is thus able to incrementally create a desired form. Examples of thermally solidifiable systems include fused deposition modeling, wax jetting, metal jetting, consumable rod arc welding, and plasma spraying.

Since most deposition materials change density with temperature, especially as they transition from a fluid to a solid, thermally solidifiable material rapid prototyping systems share the challenge of minimizing geometric distortions of the product prototypes that are produced by these density changes. Thermally solidifiable systems are subject to both "curl" and "plastic deformation" distortion mechanisms. Curl is manifest by a curvilinear geometric distortion which is induced into a prototype during a cooling period. The single largest contributor to such a geometric distortion (with respect to prototypes made by the current generation of rapid prototyping systems which utilize a thermally solidifiable material) is a change in density of the material as it transitions from a relatively hot flowable state to a relatively cold solid state.

For the simple case where an expansion coefficient is independent of temperature, the nature and magnitude of geometric distortion of sequentially applied planar layers can be estimated. Assume a linear thermal gradient dT/dz is present in a material when it is formed into a plate of thickness h in the z direction, and that the material has a constant thermal expansion coefficient α. The z direction is generally orthogonal to a support surface on which the plate is constructed. If the plate is subsequently allowed to come to some uniform temperature, it will distort, without applied stress, to form a cylindrical shell of radius r where:

$$r=(\alpha * dT/dz)^{-1} \qquad (1)$$

Curl C is defined as the inverse of the radius of curvature: $C=1/r$. An example of positive curl is shown in FIG. **1**.

Sequential layers of a thermoplastic material **104** are deposited on a base **102**, using a moving extruder **106**. As is typical in thermally solidified rapid prototypes, a series of layers are deposited sequentially in the z direction (i.e., the direction orthogonal to base **102**), with the last layer deposited always having the highest temperature. Such an additive process typically results in a geometrically accurate part which contains a thermal gradient. As the part subsequently cools and becomes isothermal, the part distorts as a result of a curling of the ends of long features.

If it is desired to make prototypes with a maximum horizontal length L and a maximum allowable geometric distortion δ, the maximum allowable temperature gradient within the part, as it is being formed, is as follows:

$$(dT/dz)_{max}=8\delta/L^2\alpha \qquad (2)$$

For example, to make 12 inch long parts to a tolerance of 0.030 inches, with a thermoplastic having an expansion coefficient of 90×10^{-6} per degree Centigrade, the maximum allowable thermal gradient in the part during formation is 18° C. per inch. Unfortunately, thermal gradients are usually much greater than 18° C. per inch in the vicinity of a part where fluid material is solidifying.

Techniques exist to reduce the impact of curl. One technique involves the heating of the ambient build environment to reduce the possible temperature differences. Another technique is to carefully choose build materials which exhibit lowest possible thermal expansion coefficients. Yet another technique is to deposit the build material at the lowest possible temperature.

Plastic deformation is a second phenomenon, unrelated to the thermal expansion coefficient, of a build material which can also produce distortion in a thermally solidifying prototype. Consider the fused deposition modeling apparatus shown in FIGS. **2**A and **2**B. In both cases, a flowable material flows out of a heated nozzle **106** and is solidifying on previously deposited, solidified material **104**. In FIG. **2**A, nozzle **106** is moving upwardly as it deposits material **104**, while in FIG. **2**B nozzle **106** moves downwardly. In FIG. **2**A, the material emerging from nozzle **106** sees less than a 90° bend as it is deposited, while in FIG. **2**B it sees more than a 90° bend. Experimentally, more distortion arises from the configuration of FIG. **2**B than from FIG. **2**A. Further, the effect is more pronounced for lower deposition temperatures. This is attributed to inelastic deformation of the elastic component of the material. The distortion is similar to the curl created in a piece of paper by dragging the paper over a sharp right angle bend.

The art is replete with various solid modeling teachings. For instance, U.S. Pat. No. 5,121,329 to Crump, and assigned to the same Assignee as this Application, describes a fused deposition modeling system. While the Crump system incorporates a heated build environment, it requires that the deposited material be below its solidification temperature, as subsequent layers of material are added. U.S. Pat. No. 4,749,347 to Vilavaara and U.S. Pat. No. 5,141,680 to Almquist et al. describe rapid prototyping systems that incorporate flowable, thermally solidifying material. Both patents teach a build environment that is maintained at and below the solidification temperature of the extrusion material.

Accordingly, it is an object of the invention to provide an improved method for rapid prototyping, wherein the method employs a thermally solidifiable material.

It is another object of the invention to provide an improved method for rapid prototyping which improves the geometric accuracy and fidelity of resulting parts.

It is a further object of the invention to provide an improved method for rapid prototyping which uses thermally solidifiable material which achieves reductions in internal stresses created in prototypes.

SUMMARY OF THE INVENTION

Data corresponding to a desired shape of a prototype is transmitted to a rapid prototyping system. The system calculates a sequence for extruding flowable material that thermally solidifies so as to create the desired geometric shape. A heated flowable modeling material is then sequentially extruded at its deposition temperature into a build environment that maintains the volume in the vicinity of the newly deposited material in a deposition temperature window between the material's solidification temperature and its creep temperature. Subsequently the newly extruded material is gradually cooled below its solidification temperature, while maintaining temperature gradients in the geometric shape below a maximum value set by the desired part's geometric accuracy.

The invention further includes a method for making a three-dimensional physical object of a predetermined shape. The steps of the method are as follows

a) computing a sequence of commands required to produce the predetermined shape of the three-dimensional physical object;

b) dispensing a thermally solidifiable material in a fluid state from an extruder into a build environment as prescribed by the sequence of commands;

c) maintaining during step b) the build environment, at least in a vicinity of the extruder, within a predetermined temperature range, the temperature range being above a solidification temperature of the thermally solidifiable material;

d) simultaneously with the dispensing step b) and in response to the sequence of commands, mechanically generating relative movement between the extruder and the build environment, so that the material accumulates to form the three-dimensional physical object;

e) concurrently with step d), adjusting temperatures within the build environment differentially so that the solidifiable material, upon which additional solidifiable material has accumulated, is cooled below a solidification temperature thereof; and

f) further solidifying the object by cooling the object below the solidification temperature.

It is preferred that the thermally solidifiable material is a thermoplastic which exhibits a glass transition temperature and that step c) maintains the temperature of the build environment below the glass transition temperature.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows typical prototype distortion due to thermal shrinkage of a solidifiable material.

FIGS. **2**A and **2**B shows the distortion effect which arises from inelastic deformation of the elastic component of a solidifiable material.

FIGS. **3**A, **3**B and **3**C illustrate plots of changes in specific gravity, stress relaxation modulus and viscosity versus temperature for an ABS (acrylonitrile-butadiene-styrene) thermoplastic.

FIG. **4** is a process flow diagram for a rapid prototyping system incorporating the method of the invention.

DETAILED DESCRIPTION OF THE INVENTION

This invention is based on the recognition that there is a transition region between a material's fluid state and it's

solid state. How broad a temperature range that encompasses the transition region varies with the type of material being extruded. Crystalline materials will tend to have sharper transition regions, while glassy materials will exhibit broader transition regions. However, crystalline materials in the solid phase have temperature-dependent creep rates that increase markedly as the melting point of the material is approached. Hereafter, the description will primarily consider the characteristics of glassy thermoplastics, however the invention is also applicable to mixed phase and crystalline materials.

FIGS. **3**A–**3**C show three graphs of temperature versus material properties of an ABS thermoplastic. FIG. **3**A shows the variation of density of ABS with temperature at one atmosphere. The plot is nearly piece-wise linear, and the place where the two lines meet (i.e., point X) is the glass transition temperature for the material. This point is roughly equivalent to the melting point of a crystalline solid.

FIG. **3**B illustrates the variation of the stress relaxation modulus of an ABS thermoplastic 300 seconds after stress is applied. This data is produced on a commercial rheometer by applying a fixed strain to a test part and measuring the time evolution of the stress. Practically speaking, this is an effective method for determining at what temperature the material is a solid. 300 seconds was chosen, after application of an initial strain, as a reasonable interval because it is typical for a deposition time of a layer. If a rapid prototyping method has a deposition rate that is substantially different, the time for acquiring the stress relaxation data should be changed accordingly.

FIG. **3**B shows that ABS has very little creep over 300 seconds, for temperatures up to about 70° C. This temperature is therefore defined as the solidification temperature. The creep rate increases, at first gradually and then abruptly, as the glass transition temperature is reached. By the time the material is at the glass transition temperature, it will not support an applied stress over an extended time period (while over a time period on the order of a second, it still appears somewhat stiff).

Labeled as the creep relaxation temperature is the point at which the stress relaxation modulus has dropped by a factor of 10 from its low temperature limit. At that point the material is just sufficiently solid that modeling can occur, however the material has a high enough creep rate that internal stresses can relax without impacting part geometry.

FIG. **3**C shows the variation of viscosity of ABS with temperature. The plot indicates that the deposition temperature needs to be in the vicinity of 270° C. for the material to be sufficiently flowable to be sequentially deposited to build up a part. Further, the material undergoes a substantial density change as it solidifies, which leads to the mechanical distortions discussed earlier. Finally, FIG. **3**C makes it clear that viscosity is not a sufficient measure of flowability to determine at what temperature the material is a solid.

It has been determined that by maintaining a previously deposited material (in a rapid prototyping system utilizing thermal solidification) within a specific temperature window, that stresses present in the deposited material are relieved and geometric distortions reduced. At least in the vicinity of where newly deposited material will be applied, the previously deposited material must be maintained at a temperature that is preferably in a range between the material's solidification temperature and its creep relaxation temperature. More preferably, the temperature should be maintained closer to the creep relaxation temperature. In the case of ABS, the temperature window falls between approximately 70° C. and approximately 90° C. In general, an entire build layer (outside of the immediate region of the extrusion nozzle) should be maintained above the material's solidification temperature and below the material's creep relaxation temperature.

The aforementioned temperatures are identified from stress relaxation measurements on sample blocks of the material. By maintaining the temperature of the resulting model within the aforesaid range, a balance is struck between the model being so weak that it droops and the model being so stiff that curl stresses (as described above) cause geometric distortions. Further, inherent stresses are allowed to relax, leading to more dimensionally accurate models.

While it is necessary for the previously deposited material, in the vicinity of newly deposited material, to be at a temperature within the aforesaid deposition temperature window, it is not required for the entire deposited part to within that window. As prescribed by equation 2 above, regions of the previously deposited material can be below the defined solidification temperature as long as the thermal gradient within those regions is less than that required to meet a defined accuracy specification.

Once the entire prototype model has been completed, it needs to be cooled so that it is everywhere below the material's solidification temperature, before it is handled or significantly stressed. The cooling rate should be slow enough that the thermal gradient limit set by equation 2 is not violated.

FIG. **4** shows a preferred process of building prototypes in accordance with the invention. Data corresponding to the desired shape of the prototype is transmitted to the rapid prototyping system. The system calculates a sequence for extruding flowable material that thermally solidifies so as to create the described geometric shape (box **110**). A heated flowable modeling material is then sequentially extruded at its deposition temperature into a build environment that maintains the build volume in the vicinity of the newly deposited material in a deposition temperature window defined by the material's solidification temperature and it's creep temperature (box **112**). Calculation step **110** need not be completed before deposition step **112** begins.

The newly extruded material is thereafter gradually cooled below the material's solidification temperature while maintaining temperature gradients below a maximum value set by the desired part's geometric accuracy (box **114**).

It should be understood that the foregoing description is only illustrative of the invention. Various alternatives and modifications can be devised by those skilled in the art without departing from the invention. Accordingly, the present invention is intended to embrace all such alternatives, modifications and variances which fall within the scope of the appended claims.

What is claimed is:

1. A method for making a three-dimensional physical object of a predetermined shape under control of a control system, said method employing a thermally solidifiable material having a solidification temperature and a creep relaxation temperature, said method comprising the steps of:

a) dispensing said thermally solidifiable material in a fluid state from an extruder into a build region having at least a local region temperature that exceeds the solidification temperature of the thermally solidifiable material;

b) simultaneously with the dispensing of the said thermally solidifiable material, and in response to said control system, generating relative movement between the extruder and a support in the build region, so that the said thermally solidifiable material accumulates on said support to form a three-dimensional physical object; and

c) solidifying said thermally solidifiable material by cooling said local region temperature and said material below the solidification temperature of the material.

2. The method of claim **1**, wherein the thermally solidifiable material is a thermoplastic which exhibits a glass transition temperature.

3. The method of claim **2**, wherein the local region temperature of the build environment, at least during step b), is below the glass transition temperature.

4. The method of claim **1**, wherein the creep temperature is a point at which the stress relaxation modulus of the thermally solidifiable material has dropped by a factor of 10 from its low temperature limit.

5. The method of claim **1**, wherein the local region encompasses at least a most recently deposited layer of said thermally solidifiable material.

6. The method of claim **5**, wherein the local region temperature of the build environment is maintained, at least during step b), below the creep relaxation temperature of said thermally solidifiable material.

7. The method of claim **1**, wherein concurrent with said cooling of said local region and said material below the solidification temperature of the material during step c), a rate of temperature change versus position in the said physical object is maintained below a threshold value.

8. The method of claim **1**, wherein the thermally solidifiable material is acrylonitrile-butadiene-styrene.

9. A method for making a three-dimensional physical object of a predetermined shape comprising the steps of:

a) computing a sequence of commands required to produce said predetermined shape of the three-dimensional physical object;

b) dispensing a thermally solidifiable material in a fluid state from an extruder into a build environment as prescribed by the sequence of commands;

c) maintaining during step b) the build environment, at least in a vicinity of the extruder, within a predetermined temperature range, said temperature range being above a solidification temperature of the thermally solidifiable material;

d) simultaneously with the dispensing step b) and in response to the sequence of commands, mechanically generating relative movement between the extruder and the build environment, so that the said material accumulates to form the three-dimensional physical object;

e) concurrently with step d), adjusting temperatures within the build environment differentially so that the solidifiable material, upon which additional solidifiable material has accumulated, is cooled below a solidification temperature thereof; and

f) further solidifying the said object by cooling said object below said solidification temperature.

10. The method of claim **9**, wherein the thermally solidifiable material is a thermoplastic which exhibits a glass transition temperature and step c) maintains the temperature of the build environment below the glass transition temperature.

11. The method of claim **9**, wherein the thermally solidifiable material is acrylonitrile-butadiene-styrene.

* * * * *

EXHIBIT C

US006004124A

United States Patent [19]

[11] **Patent Number: 6,004,124**

[45] **Date of Patent: Dec. 21, 1999**

Swanson et al.

[54] **THIN-WALL TUBE LIQUIFIER**

[75] Inventors: **William J. Swanson**, St. Paul; **Paul E. Hopkins**, Savage, both of Minn.

[73] Assignee: **Stratasys, Inc.**, Eden Prairie, Minn.

[21] Appl. No.: **09/013,388**

[22] Filed: **Jan. 26, 1998**

[51] **Int. Cl.**[6] **B29C 41/02**; B29C 41/46

[52] **U.S. Cl.** **425/375**; 264/308

[58] **Field of Search** 425/375; 264/308

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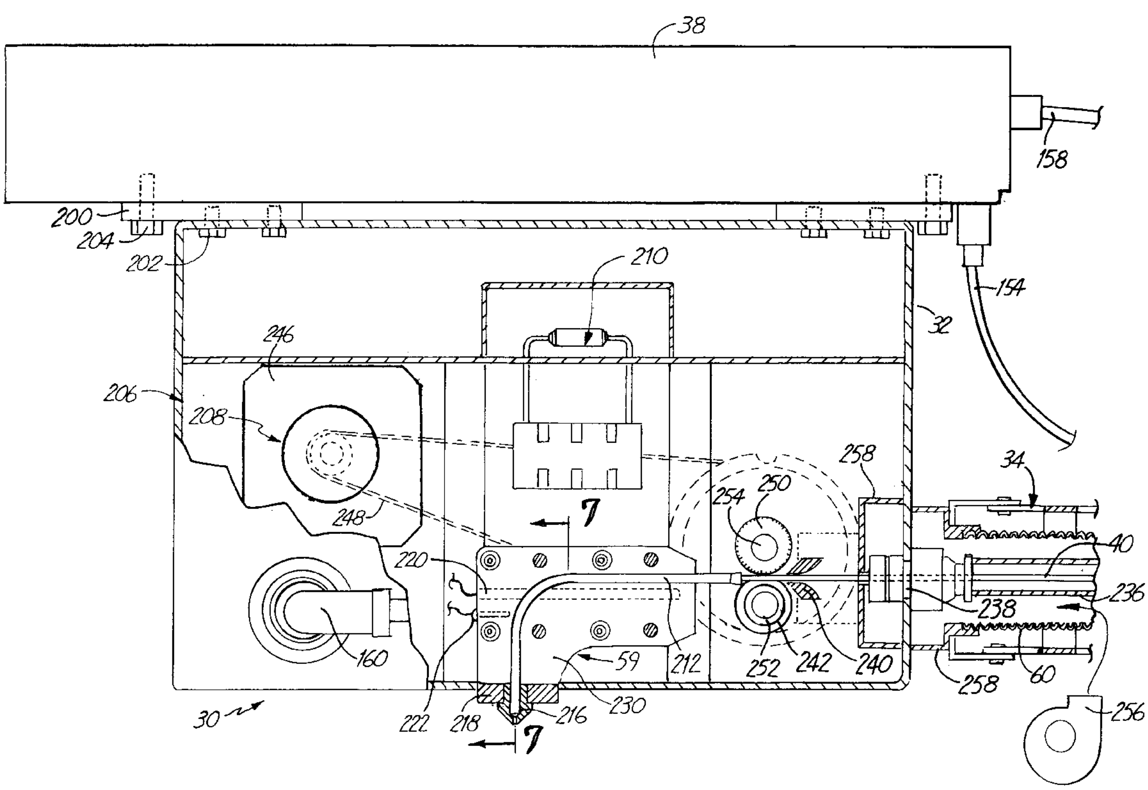
Primary Examiner—Robert Davis
Attorney, Agent, or Firm—Kinney & Lange, P.A.

[57] **ABSTRACT**

A rapid prototyping system has a liquifier carried by a extrusion head. The liquifier is formed of a single piece of thin-wall tubing preferably made of metal, encased in a heating block. The thin-wall tube has a inlet end for receiving a filament of molding material and an outlet end for delivering the material in liquid form. A first section of the tube adjacent the inlet end functions as the entrance or cap zone. This first section of the tube is exterior to the heating block. The tube has a second section which passes through the heating block forming a heating zone. A nozzle can be formed by swaging the outlet end of the tube to a nozzle geometry, or, a nozzle may be brazed or welded to the outlet end of the tube. The heating block preferably contains a heating element in heat exchange relation to the second section of the tube to heat the filament to a temperature just above its solidification temperature. The extrusion head may alternatively carry two liquifiers that share a common nozzle, for receiving and dispensing two different materials.

32 Claims, 9 Drawing Sheets



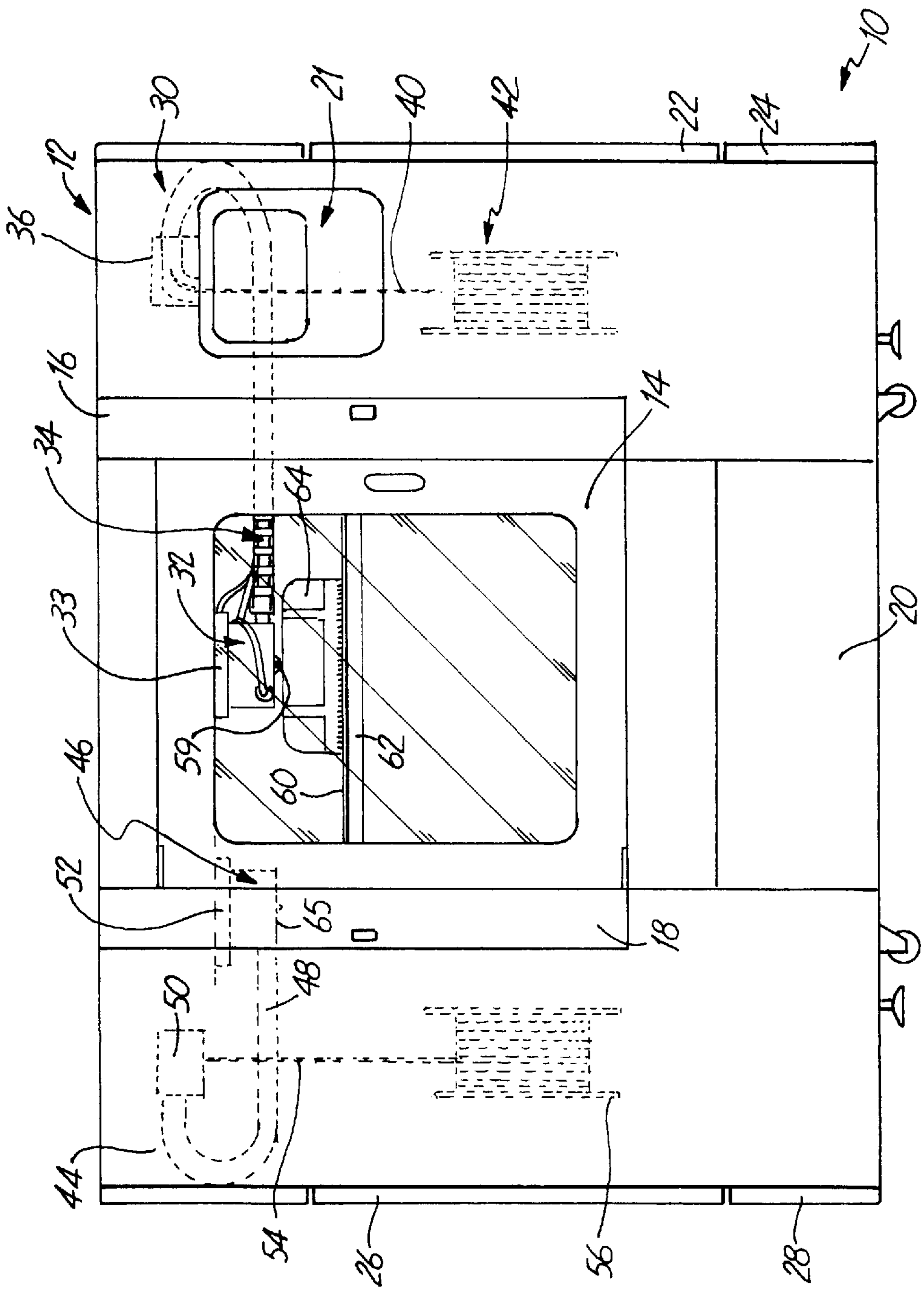

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Fig. 1

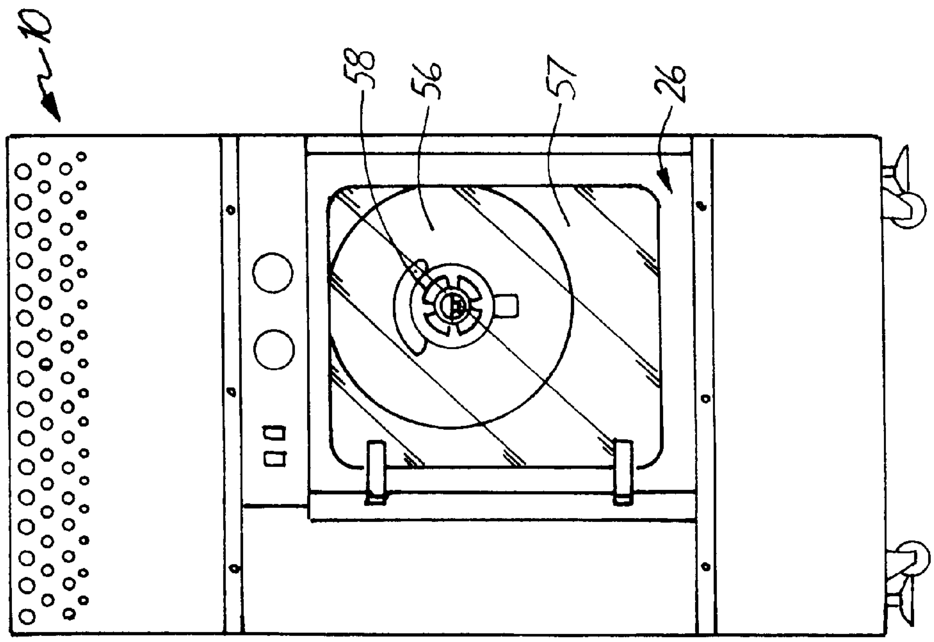


Fig. 3

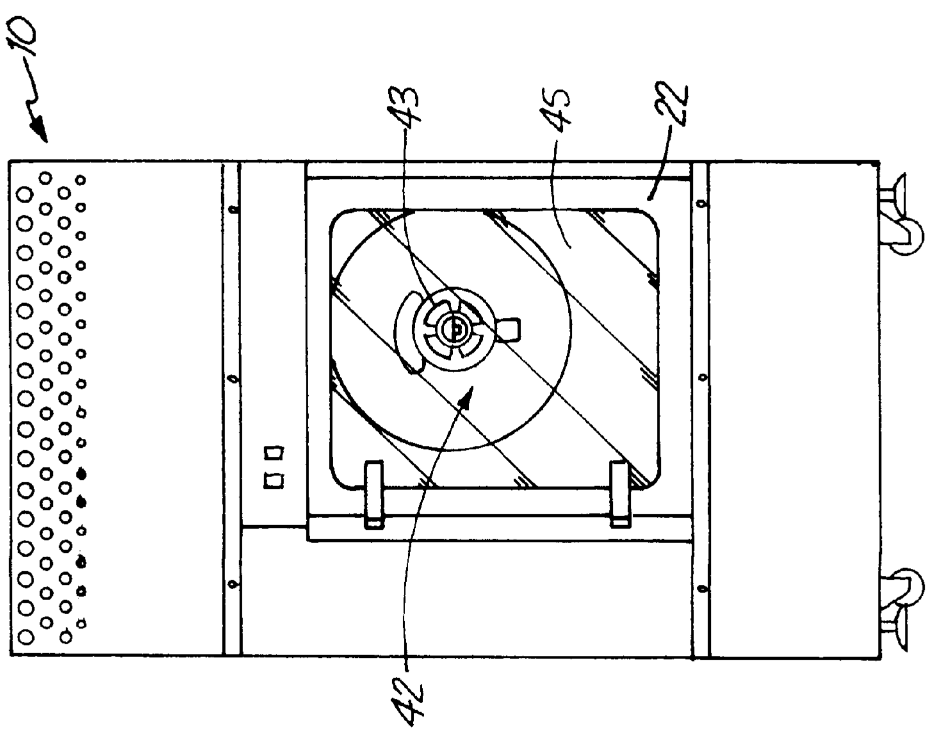
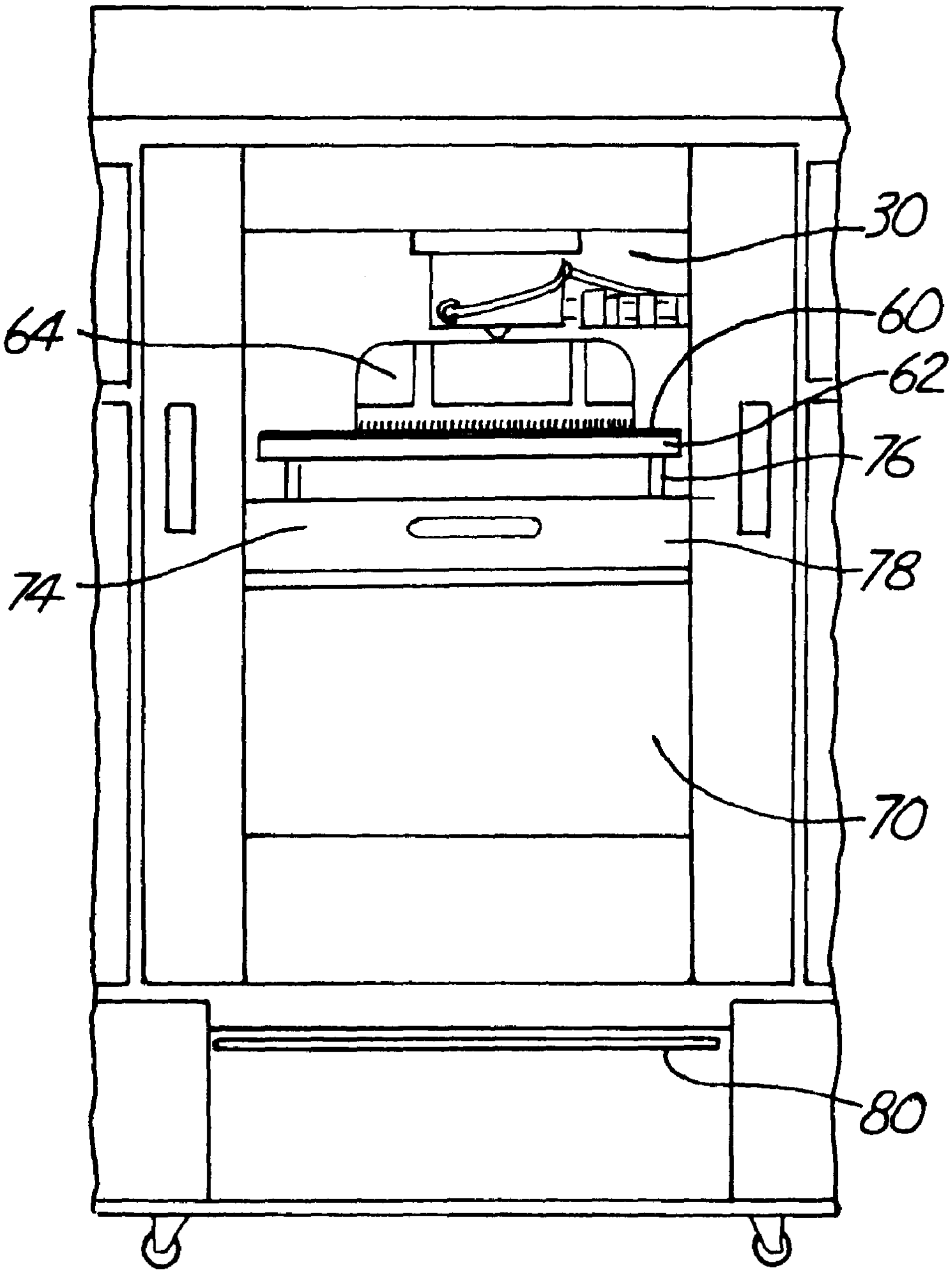
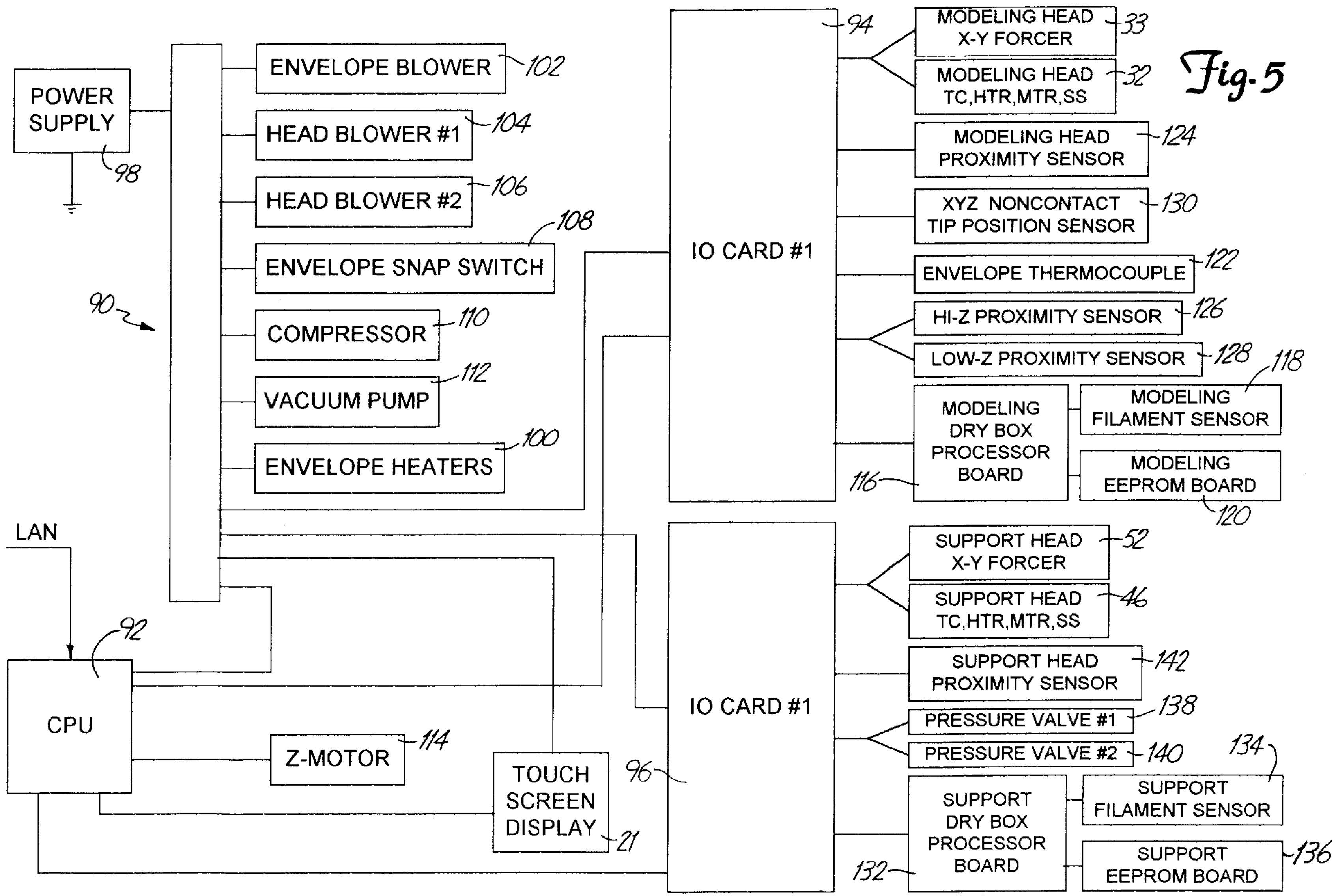


Fig. 2

Fig. 4




POWER SUPPLY
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Z-MOTOR
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32
MODELING HEAD PROXIMITY SENSOR
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LOW-Z PROXIMITY SENSOR
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MODELING DRY BOX PROCESSOR BOARD
116
MODELING FILAMENT SENSOR
MODELING EEPROM BOARD
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SUPPORT HEAD TC,HTR,MTR,SS
46
SUPPORT HEAD PROXIMITY SENSOR
142
PRESSURE VALVE #1
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PRESSURE VALVE #2
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134
SUPPORT DRY BOX PROCESSOR BOARD
132
SUPPORT FILAMENT SENSOR
SUPPORT EEPROM BOARD
136

Fig. 5

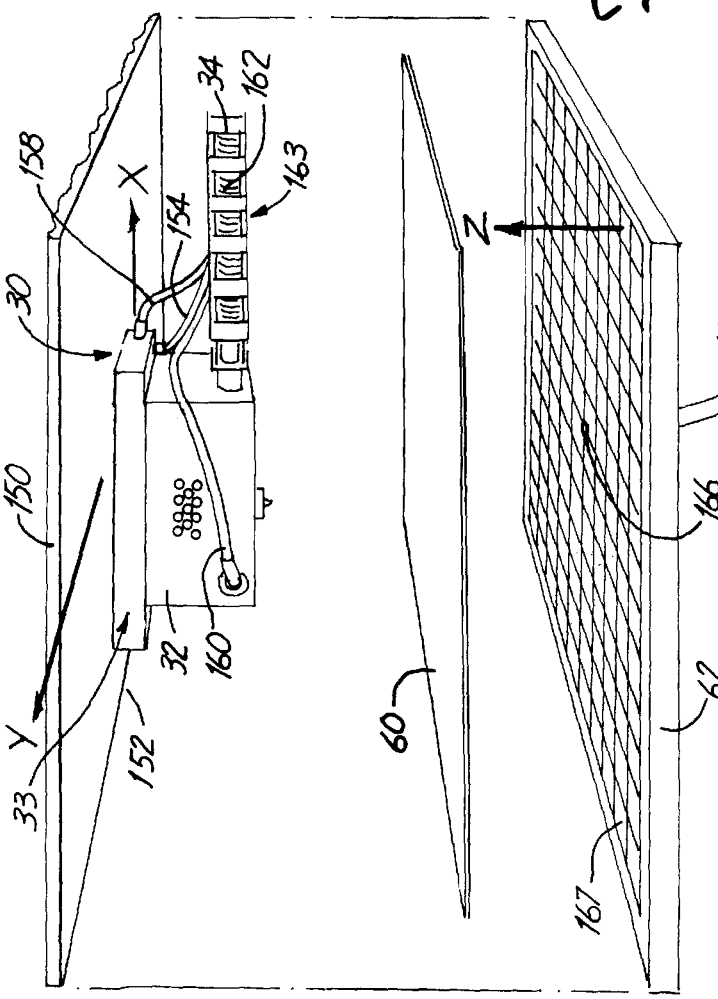

Fig. 6

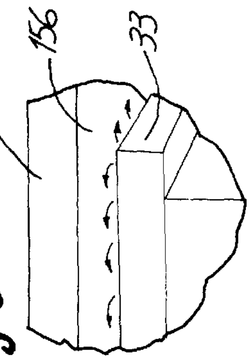

Fig. 6B

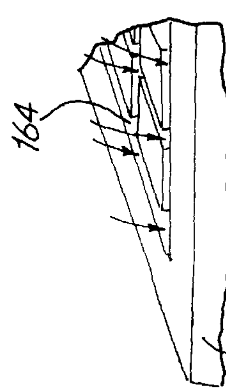

Fig. 6A

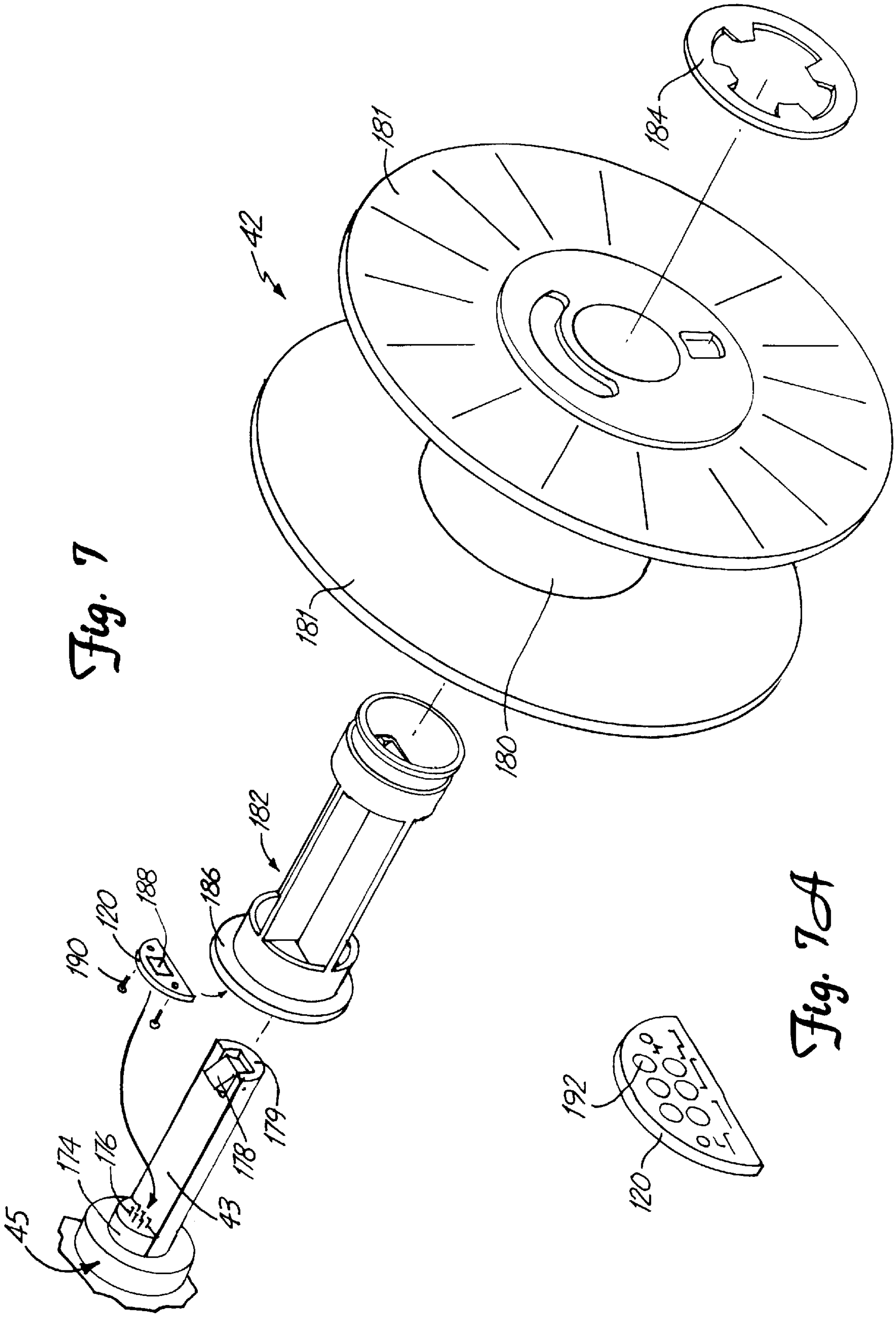
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Fig. 7

Fig. 7A

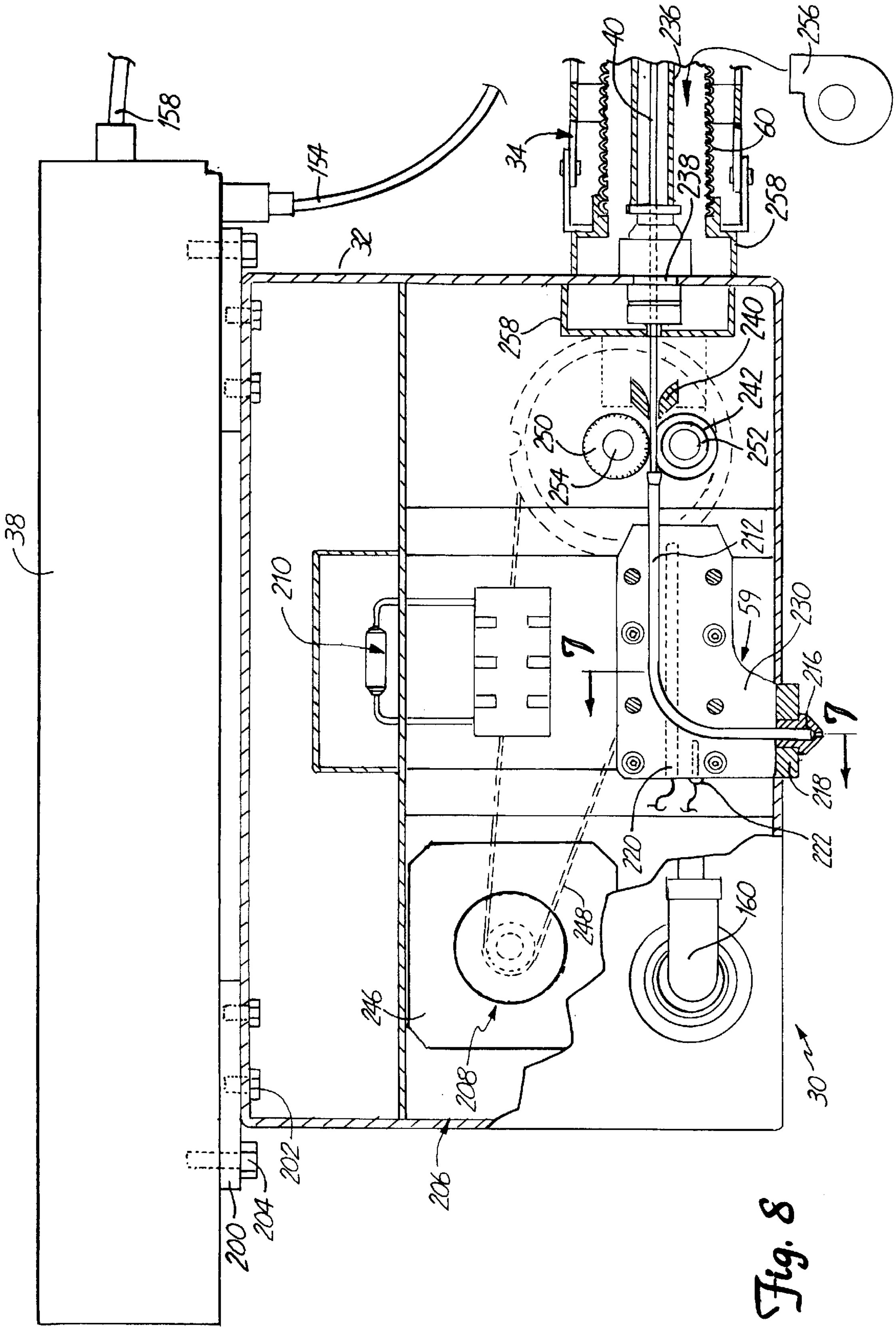
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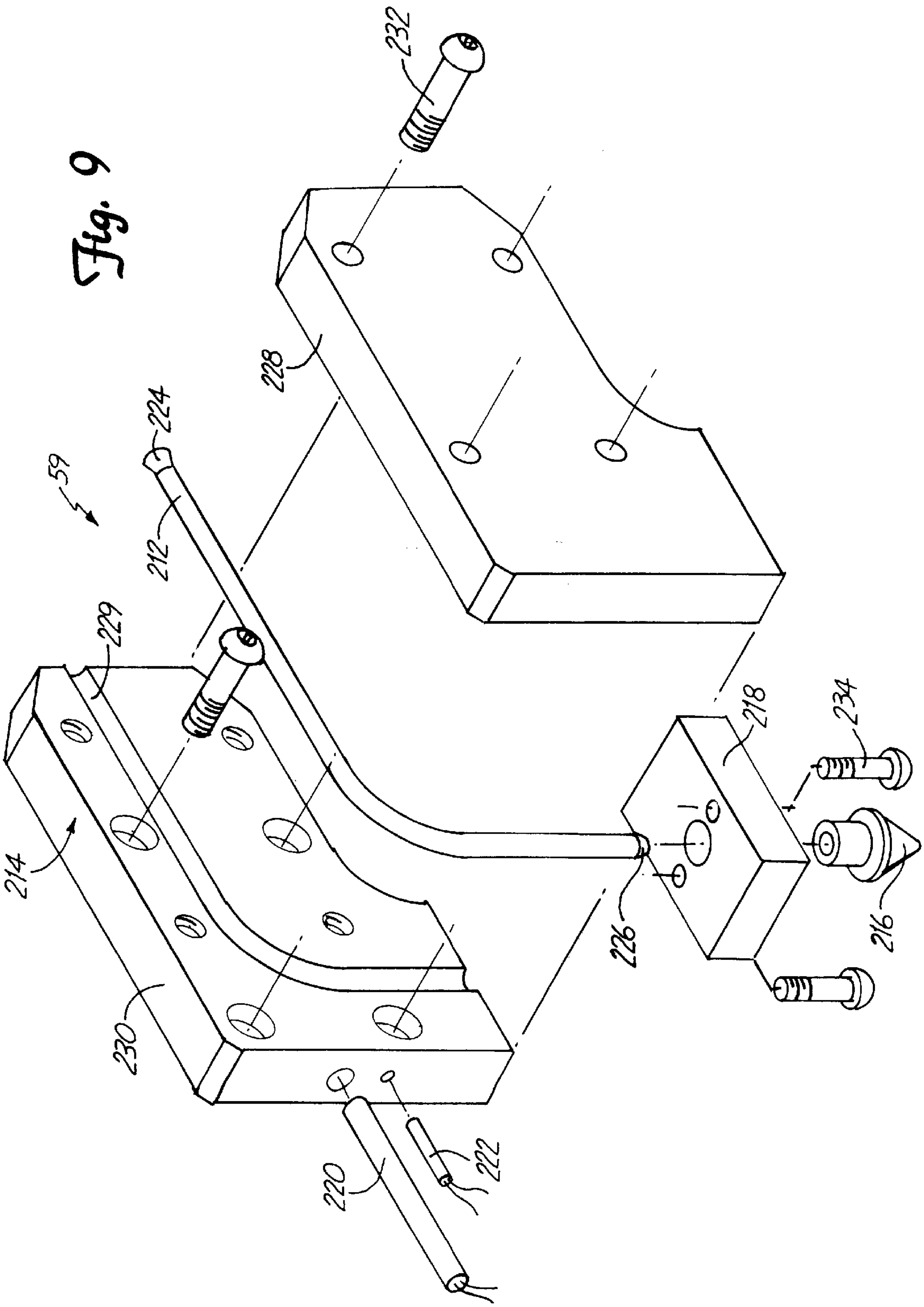
Fig. 8

Fig. 9



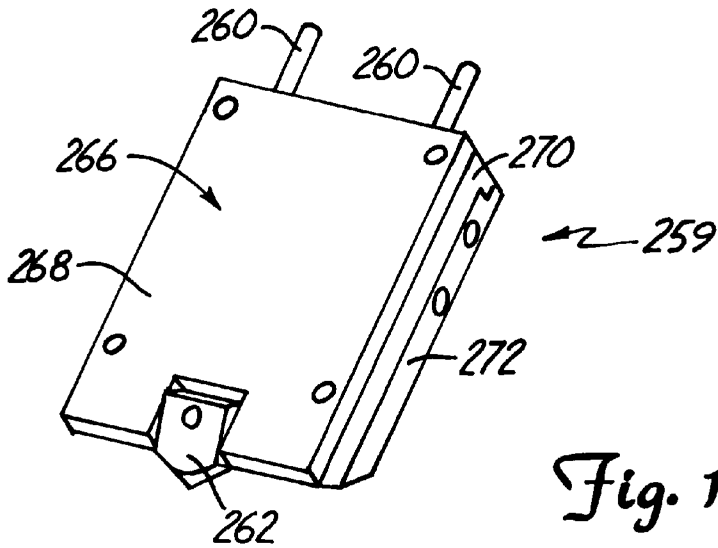


Fig. 10A

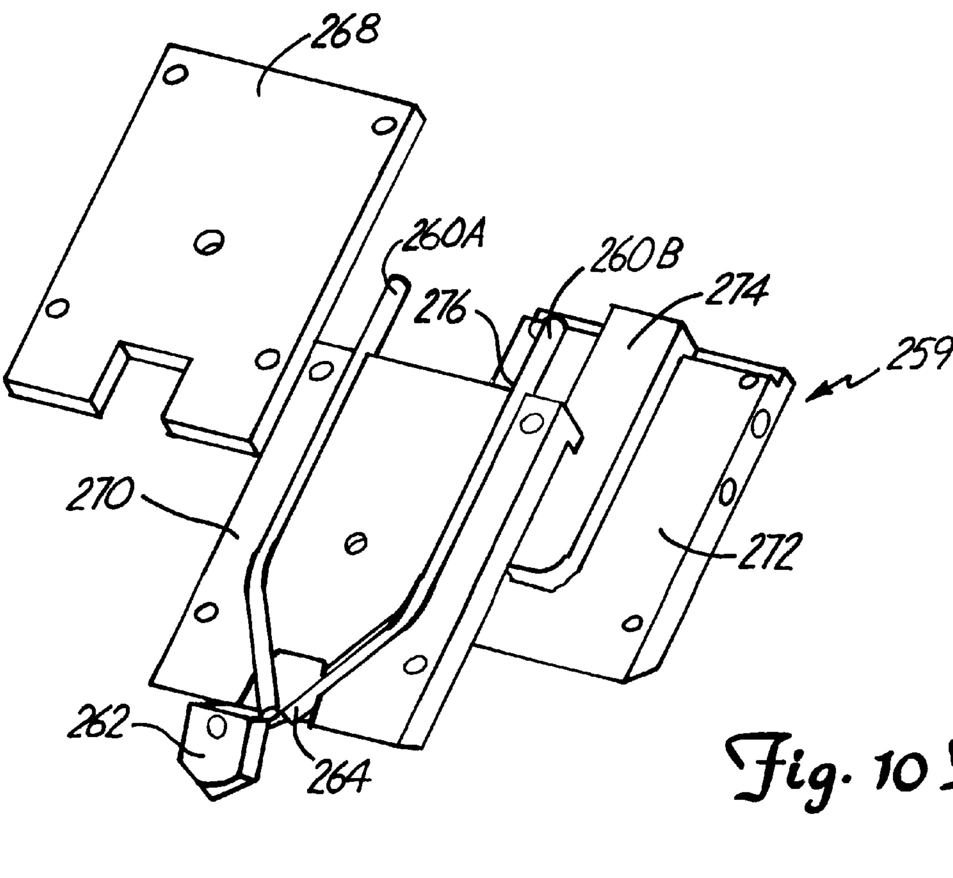


Fig. 10B

THIN-WALL TUBE LIQUIFIER

BACKGROUND OF THE INVENTION

This invention relates to a dispensing head for depositing layers of solidifying material in a desired pattern to form three-dimensional physical objects. One useful application for such a device is rapid prototyping of models or objects. The modeling material is selected and its temperature is controlled so that it solidifies upon extrusion from the dispensing head onto a base, with the build-up of multiple layers forming the desired article.

A rapid prototyping system involves the molding of three-dimensional objects based upon design data which is provided from a computer aided design (CAD) system. Examples of apparatus and methods for rapid prototyping of three-dimensional objects by depositing layers of solidifying material are described in Crump U.S. Pat. No. 5,121,329, Batchelder et al. U.S. Pat. No. 5,303,141, Crump U.S. Pat. No. 5,340,433, Batchelder U.S. Pat. No. 5,402,351, Batchelder U.S. Pat. No. 5,426,722, Crump et al. U.S. Pat. No. 5,503,785, and Abrams et al. U.S. Pat. No. 5,587,913, all of which are assigned to Stratasys, Inc. The rapid prototyping systems disclosed in the '329, '433 and '785 patents ("Crump patents") describe an extrusion head which receives a solid state material used to form three-dimensional articles, heats the material to just above its solidification temperature, and dispenses the material as a fluid onto a base.

Various embodiments of the extrusion head are shown in the Crump '433 patent. Each embodiment includes a liquifier which consists of three zones: an entrance zone or cap, a heating zone or body and a nozzle. A first embodiment is shown in FIG. **3** of the '433 patent. FIG. **3** shows a liquifier within a extrusion head having a seal ring (i.e., a cap), a heating head (i.e., heating zone) and a nozzle. The seal ring receives a supply rod of solid material. An electric heater within the heating head heats the supply rod to a temperature exceeding its solidification temperature, reducing it to a liquid state. The liquid material then flows into the nozzle through a nozzle flow passage, and is dispensed through a nozzle dispensing outlet.

A second embodiment of the extrusion head is shown in FIG. **5** of the Crump '433 patent. In this embodiment, the supply material is in the form of a flexible strand in solid form. The flexible strand of material shown in FIG. **5** is fed through a guide sleeve to a extrusion head. The extrusion head contains a supply chamber in a top portion and a liquifier in a bottom portion. Drive rollers within the supply chamber introduce the flexible strand into the liquifier. The liquifier within the extrusion head includes a seal ring (i.e., a cap), a material supply and flow passage (i.e., heating zone) and a dispensing outlet orifice (i.e., a nozzle). The flexible strand is advanced into the liquifier through the seal ring, which provides a hydraulic seal around the internal surface of the flow passage. A heater in the form of a sleeve containing a heating coil is positioned around the flow passage and the orifice to heat the strand to a fluid state in the passage. The material is dispensed in a fluid state through the orifice.

A third embodiment of the extrusion head is shown in FIG. **13** of the Crump '433 patent. As with the embodiment shown in FIG. **5**, the material is supplied in the form of a flexible strand in solid form. The strand is advanced into a extrusion head through a guide sleeve. A strand advance mechanism comprising a pair of motor-driven feed rollers or pullies and advances the strand into the liquifier. The liquifier of FIG. **13** is comprised of a tubular guide member, a seal ring, a liquifier nozzle and a removable tip. The tubular guide member and seal ring together form the cap zone. The tubular guide member is made of highly conductive metal, such as aluminum or silver. It dissipates heat rapidly to maintain the flexible strand at a suitable temperature during its movement from the strand advance mechanism into the heating zone. To further dissipate heat from the guide member, a blower may be used to circulate air into the extrusion head, around the guide member. A cooling fin extending from the guide member in an "L"-shape is additionally utilized to enhance the heat dissipation from the guide member. At its lower end, the guide member is supported on the seal ring. The seal ring is made out of heat-insulating plastic to serve as a thermal seal. The liquifier nozzle surrounded by a heating coil and an outer insulation sleeve provides a heating zone in which the strand material is melted. The liquifier nozzle (i.e., heating tube) is made of heat-conducting material such as silver or preferably aluminum. The removable tip is attached to the bottom end of the liquifier nozzle by a threaded connection.

A fourth embodiment of the extrusion head is shown in FIG. **6** of the Crump '433 patent. In this embodiment, multiple materials are dispensed through separate passages into a single discharge outlet. The embodiment of FIG. **6** allows utilization of different materials to form different layers of the same article.

The Crump '785 patent discloses an extrusion head carrying two liquifiers, each having its own nozzle. The liquifiers of the '785 patent each have a cap at a receiving end, secured by a mounting ring to a tubular dispenser (i.e., heating tube). A heating coil is wrapped around each tubular dispenser to heat and melt a filament of material. In each liquifier, the material is provided in a fluid state to a dispensing nozzle and discharged through a nozzle tip. Filament is conveyed to each liquifier from a supply spool by a pair of pinch rollers driven by stepper motors.

In the aforementioned liquifiers, the cap region serves as the transition zone for the modeling material where at the entrance to the cap the temperature is below the softening point of the material and the outlet of the cap is above the temperature required to pump the material in a semi-liquid state. This requires a change in temperature of up to 250° Celsius over the length of the cap. Ideal properties for the cap are a high thermal resistivity in the axial direction and low thermal resistivity in the radial direction. The previous designs, such as those described in the Crump patents, used high temperature thermoplastics or thermoset plastics such as Dupont "Vespel" SP-1, for the cap to accomplish these goals. These caps are expensive, have temperature limitations, and require a sealing mechanism between the cap and the heating body, which is typically formed of aluminum. The caps and seal are prone to leakage.

It would be desirable to form the cap zone of the liquifier out of the same medium used to form the liquifier body. A medium that is inexpensive, that allows bends in the liquifier path to be easily made, and that can further be used to form the nozzle zone would also be desirable.

SUMMARY OF THE INVENTION

The present invention is an improved liquifier for use in the extrusion head of a rapid prototyping system of the type generally shown in the Crump patents. The present invention provides a thin-wall tube liquifier formed of a single piece of thin-wall tubing encased in a heating block. The tube acts as both the heating zone and the cap zone of the liquifier. In the preferable embodiment, the tube is made of metal. The nozzle zone can be formed by swaging the metal tube to a nozzle geometry, or, it may be brazed or welded to the bottom of the tube. The heating block is made of heat conductive material, such as aluminum or beryllium copper (BeCu).

The thin-wall tube has a inlet end for receiving a filament of molding material and an outlet end for delivering the material in liquid form. A first section of the tube adjacent the inlet end functions as the entrance or cap zone. This first section of the tube is exterior to the heating block. The tube has a second section which passes through the heating block forming a heating zone. The nozzle connects to the outlet end of the tube. The heating block preferably contains a heating element in heat exchange relation to the second section of the tube to heat the filament to a temperature just above its solidification temperature.

The filament is preferably of a very small diameter, on the order of 1/16th inch. The cap zone of the tube must dissipate heat rapidly to maintain the flexible strand at a suitable temperature during its movement into the heating zone, so that the strand will not become limp and buckle. A stainless steel tube having a wall thickness in the range of 0.008–0.015 inches is suitable and inexpensive for this purpose. The interior diameter of the tube is preferably on the order of 0.07 inches.

The filament may be fed or advanced in various ways to the liquifier. A pair of power-driven pinch rollers is a preferred advance mechanism for gripping and advancing the filament.

The heating block is preferably comprised of a first and a second section, which are mechanically detachable to allow access to and removal of the tube. This heating block design facilitates maintenance and replacement of the tube.

An alternative embodiment of the present invention provides two liquifiers that share a common nozzle for receiving two filaments of diverse materials and delivering each in liquid form. In this embodiment, two thin-wall tubes of the type described with reference to the first embodiment are braised or welded to a common nozzle. The heating block preferably has three mechanically detectable vertical sections, two outer sections and one interior section which positions the tubes and nozzle. One of the outer sections preferably contains a heating element in heat exchange relation to the second section of each tube.

The foregoing invention provides several advantages over the previous liquifier designs. It eliminates the need for a seal between the liquifier body and cap zones, and is simpler and less expensive to manufacture. The liquifier of the present invention further allows for simple or complex bends in the liquifier path to be easily made. Further, the nozzle zone of the liquifier can be formed out of the tube as well, by swaging the tube to the nozzle geometry. The tube is easily accessible by mechanically detaching the first and second sections of the heating block. The liquifier of the present invention can additionally be modified to dispense two materials through a common nozzle. This provides a system that is lighter, cheaper to manufacture, and easier to control than systems with two separate liquifiers.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is an exterior front elevation view of the preferred embodiment of the invention, showing the system in a build state.

FIG. **2** is an exterior elevation view of the right side of the preferred embodiment of the invention.

FIG. **3** is an exterior elevation view of the left side of the preferred embodiment of the invention.

FIG. **4** is a front elevation view of the prototyping envelope, showing the system in a build state.

FIG. **5** is an electrical block diagram of the control system of the preferred embodiment of the invention.

FIG. **6** is a partially exploded perspective view of the prototyping envelope showing the modeling extrusion head in a build position.

FIG. **6**A is a detailed view of a portion of FIG. **5** illustrating the vacuum platen grooves.

FIG. **6**B is a detailed view of a portion of FIG. **5** illustrating the air bearing of the linear motor.

FIG. **7** is an exploded view of the filament spindle and filament spool shown in FIGS. **2** and **3**.

FIG. **7**A is a perspective view of the outward face of the EEPROM board.

FIG. **8** is a front elevation of the modeling extrusion head, with portions shown in sectional.

FIG. **9** is an exploded view of the liquifier.

FIGS. **10**A and **10**B show an alternative embodiment of the liquifier.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In the preferred embodiment, the rapid prototyping system **10** is contained within a cabinet **12**, as shown in FIG. **1**. The cabinet **12** has doors and covers located on a front, left and right sides thereof On the front of cabinet **12**, there is an envelope door **14**, a modeling waste tray door **16** to the right of envelope door **14**, a touch screen display panel **21** to the right of modeling waste tray door **16**, a support waste tray door **18** to the left of envelope door **14**, and platform cover **20** below envelope door **14**. A modeling drybox door **22** and an electronics bay cover **24** are located on the right hand side of cabinet **12**. A support drybox door **26** is located above a compressor bay cover **28** on the left hand side of cabinet **12**.

The upper right hand side of cabinet **12** houses a modeling extrusion apparatus **30**, which comprises a modeling extrusion head **32** attached below a modeling x-y forcer **33** and connected to the end of a modeling arm **34** which rotates about a modeling pivot joint **36**. Modeling extrusion apparatus **30** receives a filament of modeling material **40** from a modeling filament spool **42** located in a modeling drybox **45** (FIG. **2**) below pivot joint **36** and accessible through modeling drybox door **22**. Drybox **45** maintains low humidity conditions to optimize the condition of filament **40**. Modeling extrusion apparatus **30** is used to dispense modeling material in layers onto a substrate **60**. Modeling filament spool **42** mounted on a modeling spindle **43** in drybox **45** is more clearly shown in FIG. **2**.

The left-hand side of cabinet **12** houses a support extrusion apparatus **44**, which is comprised of a support extrusion head **46** attached below a support x-y forcer **52** and connected to the end of a support arm **48** which rotates about a support pivot joint **50**. Support extrusion apparatus **44** receives a filament of support material **54** from a support filament spool **56** located in a support filament drybox **57** (FIG. **3**) beneath support pivot joint **50** and accessible through support drybox door **26**. Drybox **57** maintains low humidity conditions to optimize the condition of filament **54**. Support extrusion apparatus **44** is used to dispense support material in layers. Support filament spool **56** mounted on a support spindle **58** in drybox **57** is more clearly shown in FIG. **3**.

Modeling material extruded in layers by modeling extrusion apparatus **30** forms object **64**. The support material is used to support any over-hanging portions as the object is being built up. In building an object, over-hanging segments or portions which are not directly supported in the final geometry by the modeling material require a support structure. Support filament **54** is supplied to support extrusion head **46** which deposits material to provide the required support. The support material, like the modeling material, is deposited in multiple layers.

In building an object, only one extrusion apparatus at a time is in an active, extruding state. In FIG. **1**, the system **10** is shown building a three-dimensional object **64**, with modeling extrusion apparatus **30** in an active build state, and support extrusion apparatus **44** in a home rest position. When modeling extrusion apparatus **30** is in an active state, modeling filament **40** travels through arm **34** to extrusion head **32**, where is it heated to a liquid state. Layers of modeling material in a molten state are deposited by head **32** through a liquifier **59** protruding through a bottom suface of head **32**, onto substrate **60**. Substrate **60** is supported upon a vacuum platen **62** and held in place by vacuum forces. When support extrusion apparatus **44** is in an active build state, support head **46** similarly receives support filament **54** via arm **48**, and heats it to a liquid state. Layers of support material in a molten state are deposited by head **46** through a liquifier **59** protruding through a bottom surface of head **32**, onto substrate **60**.

The filaments of modeling and support materials are each a solid material which can be heated relatively rapidly above its solidification temperature, and which will very quickly solidify upon a small drop in temperature after being dispensed from the extrusion head. A composition having a relatively high adhesion to itself upon which it is deposited when hot is selected for the modeling material. A composition having a relatively low adhesion to the model material upon which it is deposited is selected for the support material, so that the support material forms a weak, breakable bond with the modeling material and to itself When the object is complete, the support material is broken away by the operator, leaving the object formed of modeling material intact.

The modeling material is preferably a thermoplastic material. Other materials that may be used for the modeling material filament include bees wax, casting wax, machinable and industrial waxes, paraffin, a variety of thermoplastic resins, metals and metal alloys. Suitable metals include silver, gold, platinum, nickel, alloys of those metals, aluminum, copper, gold, lead, magnesium, steel, titanium, pewter, manganese and bronze. Glass, and particularly Corning glass would also be satisfactory. Chemical setting materials, including two-part epoxies would also be suitable. A modeling material found to be particularly suitable is an acrylonitrile-butadiene-styrene (ABS) composition. A material found to be particularly suitable for the support material is an acrylonitrile-butadiene-styrene (ABS) composition with a polystyrene copolymer added as a filler (up to about 80%) to create a lower surface energy of the ABS composition, and to provide a lower cohesion and adhesion of the material. Both filaments of material are preferably of a very small diameter, on the order of 0.070 inch. The filament may, however, be as small as 0.001 inch in diameter.

FIG. **4** shows a build envelope **70** which is the central interior region of the system **10**, accessible through envelope door **14**. In FIG. **4**, door **14**, platform cover **20**, and the adjoining face plates of cabinet **12** are removed. The envelope **70** is where a three-dimensional object is built. Envelope **70** contains a build platform **74** which comprises vacuum platen **62** supported by a set of legs **76**, which ride on a platform drawer **78**. Build platform **74** moves vertically in a z-direction within envelope **70**. Movement of build platform **74** is controlled by a z-drive chain **80**, driven by a z-motor **114** (shown schematically in FIG. **5**). Build platform **74** remains stationary during formation of a single layer. As each additional layer is deposited on substrate **60**, build platform **74** is lowered slightly so as to allow a space for forming the subsequent layer. Platform drawer **78** pulls forward to allow the operator ready access to vacuum platen **62**.

An electrical system **90**, shown schematically in FIG. **5**, controls the system **10**. A CPU **92**, together with first input/output (IO) card **94** and second input/output (IO) card **96**, control the overall operation of the electrical system **90**. CPU **92** receives instructions from the operator through communication from touch screen display **21**. Similarly, CPU **92** communicates with touch screen display **21** to display messages for the operator and to request input from the operator. CPU **92** in turn communicates with IO cards **94** and **96**. A power supply **98** supplies power to electrical system **90**.

Envelope heaters **100** and envelope blower **102** establish and maintain a temperature in the envelope **70** of approximately 80° C. An envelope thermal cutout (THCO) switch **108** carries current through the machine's main contractor actuation coil. If the temperature reaches approximately 120° C. the THCO switch opens and current through the main contractor to the system is interrupted. The head blowers **104** and **106** supply air at ambient temperature to cool the pathway of filaments **40** and **54** as they travel into modeling extrusion head **32** and support extrusion head **46**, respectively.

CPU **92** also controls a compressor **110**. Compressor **110** supplies compressed air alternately to x-y forcers **33** and **52** provides a vacuum to platen **62**. CPU **92** provides layering drive signals to selectively actuate the z-motor **114**, which drives platform **74** along the z-axis.

IO Card **94**, under the control of CPU **92**, sends and receives signals associated with modeling extrusion head **32** and the filament supply thereto. IO card **94** sends drive signals that control the movement and position of x-y forcer **33**. IO card **94** further sends and receives signals to and from modeling extrusion head **32**, which includes a thermocouple **222** (TC), a heater **220** (HTR), a motor **246** (MM) and a safety switch **210** (SS) (shown in FIGS. **8–10**). Safety switch **210** shuts down the system if the temperature in the modeling extrusion head **32** gets too high.

IO card **94** monitors data concerning modeling material filament spool **42** through communications with a modeling drybox processor board **116**. Modeling drybox processor board **116** is mounted inside of modeling filament drybox **45**. It receives data concerning the modeling filament from a modeling filament sensor **118** (located at the inlet to filament guide **236**, shown in FIG. **8**) and a modeling EEPROM board **120**, which is a circuit board carrying an electronically readable and writeable device (EEPROM **188**, shown in FIG. **7**), attached to modeling material filament spool **42**. EEPROM board **120** acts as an electronic tag with a variety of functions. It informs the control system **90** of the type of filament that is on the spool and of the lineal feet of filament on the spool. As filament **40** is wound off of the spool **42**, the CPU keeps track of how much material was commanded to be extruded, subtracts this amount from the total on the EEPROM **188** and writes the new value to the EEPROM **188**. Preferably, the data on EEPROM board **120** is encrypted so that it can be updated the CPU **92**. Filament sensor **118** senses and indicates the presence or absence of filament at the entrance to the filament feed tube. With filament remaining on the spool the operator can then grab a hold of the filament and extract it from the extrusion head **32**. Unloading of the used filament and spool and reloading of a new spool is thereby made easier.

CPU **92** receives the modeling filament data from IO card **94**. At the outset of a job, the CPU **92** will calculate whether a spool **42** or **56** contains enough filament to complete the job. Operator notification is then provided via touch screen display **21**, stating either that the filament is adequate to complete the job, or that the filament spool will need replacement and reloading during the process. Also at the outset of a job, the CPU verifies that the modeling filament material on the spool is the same material specified in object data. If these materials are not the same, an operator notification is provided via touch screen display **21**, providing the operator an opportunity to switch spools.

IO card **94** additionally monitors the temperature in the envelope **70** via signals received from envelope thermocouple **122**, and it sends signals to and from a modeling head proximity sensor **124**, a high-z proximity sensor **126**, a low-z proximity sensor **128** and an xyz noncontact tip position sensor **130**, all of which are described below.

IO card **96** serves similar functions as IO card **94**, for the support extrusion head **52** and the filament supply thereto. IO card **96** sends drive signals that control the movement and position of x-y forcer **52**. IO card **96** further sends and receives signals to and from support extrusion head **46**, which includes a thermocouple (TC), a heater (ETR), a motor (MTR) and a safety switch (SS). The safety switch SS shuts down the system if the temperature in the modeling extrusion head **46** gets too high.

IO card **96** monitors data concerning support material filament spool **56** through communications with a support drybox processor board **132**. It receives data concerning the support filament from a support filament sensor **134** and a support EEPROM board **136**, attached to support material filament spool **56**. EEPROM board **136** acts as an electronic tag, in the same manner as EEPROM board **120**. CPU **92** receives the support filament data from support processor board **132**, and uses it to provide operator information in the same manner as described above with respect to the modeling filament.

IO card **96** further controls a first pressure valve **138** and a second pressure valve **140**, which alternately open and shut to direct the flow of air from compressor **110**. When valve **138** is closed and valve **140** is open, air from compressor **110** is directed to modeling head x-y forcer **33**. When valve **138** is open and valve **140** is closed, air from compressor **110** is directed to support head x-y forcer **52**. IO card **96** in addition communicates with support head proximity sensor **142**, which is described below.

To create an object using rapid prototyping system **10**, an operator must first power up the system by pressing a power on switch (not shown), located on touch screen display **21**. The system **10** then enters a maintenance mode, in which the system executes a routine to calibrate the locations of modeling extrusion head **32**, support extrusion head **46**, and build platform **74**. The calibration is done in two phases. In the first phase, the system initializes movement boundaries for the extrusion heads and the platform. Modeling head proximity sensor **124** initializes boundaries of the modeling head **32**, and support head proximity sensor **142** initializes boundaries of the support head **44**. High-z proximity sensor **126** and low-z proximity sensor **128** together initialize the boundaries of platform **74**. In the second stage, the xyz noncontact tip position sensor **130** initializes the position of the tips of liquifiers **59** and **65**. The xyz noncontact tip position sensor **130** is a magnetic sensor imbedded in platform **74** which detects position of the liquifier tips with three displacement degrees of freedom. Tip position sensor **130** is of the type described in co-pending application Ser. No. 08/556,583, which is incorporated by reference.

After calibration is complete, the system exits the maintenance mode and enters a standby state. In the standby state, the design of a three-dimensional object **64** is input to CPU **92** via a LAN network connection (shown schematically in FIG. **5**) utilizing CAD software such as QUICKSLICE® from Stratasys, Inc., which sections the object design into multiple layers to provide multiple-layer data corresponding to the particular shape of each separate layer. After the layering data is received, the system **10** enters a warmup phase, during which the envelope **70** is heated. Upon reaching a temperature of 80° C., the system enters a build state during which it creates the three-dimensional object.

The modeling extrusion apparatus **30** is shown more particularly in FIG. **6**. Modeling extrusion apparatus **30** is movable in a horizontal plane in x and y directions. Modeling x-y forcer **33** is positioned beneath and parallel to a planer stator **150**, which contains a grid of stator elements (not shown). Together x-y forcer **33** and planer stator **150** form an electromagnetic linear stepper motor **152**. Commercially available linear stepper motors from Northern Magnetics, Inc. of Santa Clarita, Calif. are suitable. The x-y forcer **33** consists of two sets of single-axis forcers mounted at 90° to each other and permanent magnets which hold forcer **33** against the stator (not shown). A compressed air supply **154**, supplied by compressor **110**, is provided to x-y forcer **33** when modeling apparatus **30** is active. The compressed air supply **154** flows upward through x-y forcer **33** and exits through a top surface thereof, as is illustrated in FIG. **6B**. The exiting air forms an air bearing **156** between x-y forcer **33** and planer stator **150**, which allows nearly fhictionless motion of the forcer in a horizontal plane below planer stator **150**. Drive signals to x-y forcer **33** are received through an electrical supply **158** which powers a stepper motor driver located within x-y forcer **33** (not shown) to achieve motion. Ordinarily, linear stepper motors of this type exhibit abrupt jarring motions which create mechanical resonance. This resonance typically precludes use of such motors in high-precision systems such as rapid prototyping systems. As described below, an umbilical to the head creates the surprising result of providing a damping effect sufficient to allow high-precision deposition at speeds far exceeding those possible in prior art rapid prototyping systems.

Modeling extrusion arm **34** is a flexible chain carrier that is flexible in a horizontal plane and substantially rigid in other directions. Arm **34** carries within it air supply **154** and forcer electrical supply **158**. Arm **34** also carries within it a modeling extrusion head electrical supply **160** and a flexible air tube **162** which contains an ambient air supply and modeling filament **40**, as depicted in FIG. **8**. Arm **34** together with air supply **154**, forcer electrical supply **158**, extrusion head electrical supply **160** and air tube **162** containing filament **40** form an umbilical **163** to extrusion head **32**. The umbilical **163** creates the surprising result of damping the mechanical resonance of extrusion head **32** with respect to stator **30**, which is produce by acceleration and deceleration of the head **32** by forcer **33**. In the preferred embodiment, the combined weight of head **32** and x-y forcer **33** is less than or equal to approximately 8 lbs.

The resonant frequency is about 55 Hz for small oscillations and about 45 Hz for large oscillations, and the damping time to achieve 98% of the final value (which is equal to approximately 4 times the damping time constant) in this embodiment is less than or equal to about 150 ms. Oscillation and damping of mechanical resonance may be expressed as: $A=A_o \sin(\omega t+\phi)e^{-t/\tau}$, where A=amplitude, A_o=initial undamped amplitude, $w=2\pi f$, f=resonant frequency of the system, ϕ=a phase constant, t=time, and τ=damping time constant. Critical damping occurs when $\tau=1\omega$. In the preferred embodiment described, the system is approximately a factor often from being critically damped. Further damping can, therefore, be added if desired. The damping time constant is affected by the combined weight of extrusion head **32** and x-y forcer **33**. The lighter the weight, the shorter the damping time constant.

Damping of mechanical resonance is achieved primarily by frictional forces produced during movement of umbilical **163**. Alternatively, other forms of damping means can be used, such as an oscillation dissipater (or shock-absorber) carried in extrusion head **32**. Also, further damping can be produced by decreasing the resistivity of the bucking of starter **150** (such as by using copper rather than steel) to increase eddy current losses within stator **150**.

While FIG. **5** has been described as depicting modeling apparatus **30**, it should be understood that support head apparatus **44** has a similar structure and has an umbilical of the same type described with reference to modeling apparatus **30**. Specifically, support x-y forcer **52** shares the planer stator **150** such that x-y forcer **52** and stator **150** form a second linear motor. Support apparatus **44** starts from the opposite side of cabinet **12** from modeling apparatus **30**. For ease of reference, only one head is shown in detail.

Vacuum platen **62** and substrate **60** are shown in an exploded fashion in FIG. **6**. Vacuum platen **62** has a top surface **167** comprised of a grid of grooves **164**, shown in detail in FIG. **6**A. In the preferred embodiment, grooves **164** are 0.06 inches deep, 0.06 inches wide, and are **1** inch on center apart. An orifice **166** extends through the center of vacuum platen **62**. Orifice **166** receives a vacuum hose **168** which connects to vacuum pump **112**. When the system **10** is powered up, a vacuum is applied to vacuum platen **62** by vacuum hose **168** and vacuum pump **112**. The vacuum provided to platen **62** pulls air through grooves **164** to distribute the vacuum along the platen. This vacuum holds the substrate **60** against the top surface **167** of platen **62**. In the preferred embodiment, substrate **60** is a flexible sheet. A polymeric material forms a suitable flexible sheet substrate. An acrylic sheet with a thickness of about 0.06 inches has been successfully used as a substrate. When a desired object is formed, the operator can remove substrate **60** from the platen **62** by lifting one corner of the sheet and breaking the seal of the applied vacuum.

Flexible substrate **60** can be flexed away from the object to peel the substrate from the object, if there is a weak breakable bond between substrate **60** and the object. This weak, breakable bond may be formed by depositing a first layer (or layers) of modeling material followed by a second layer (or layers) of support material on the substrate **60**. The modeling material and substrate are selected so that the modeling material is fully adhesive to the substrate. In forming an object, the modeling material is deposited in one or more layers on the substrate **60**. The support material is

then deposited in one or more layers over the modeling material. The object is then built up on the support material, using a plurality of layers of modeling and/or support material. When the object is complete, vacuum is broken by lifting a corner of the substrate **60**, and the substrate **60** is removed from the platen **62** by the operator. By flexing the substrate **60**, the operator then peels the substrate **60** from the object. The first layer(s) of modeling material will remain adhered to the substrate, but the weak bond between the first layer(s) of modeling material and the second layer (s) of support material is a readily separable joint which breaks to allow removal of the substrate **60** without damage to the object.

Other flexible sheet materials may be used as substrate **60**. For example, plain or coated paper, metal foil and other polymeric materials are suitable. For high temperature support and modeling materials, a polymeric material (e.g., Kapton) or metal foil is particularly desirable.

Although a vacuum is a preferred way to achieve a releasable hold down force to hold substrate **60** against platen **62**, other means for providing a releasable hold down force can also be used. For example, substrate **60** can be held against platen **62** by an electrostatic chuck or by a weakly adhering adhesive applied to the bottom surface of the substrate **60** or the top surface of the platen **62** (or both).

FIG. **7** shows a detailed exploded view of the filament spool and spindle shown in FIGS. **2** and **3**. The mechanical configuration of the filament spool and spindle is identical for both the modeling filament and the support filament. For convenience of reference, FIG. **7** is directed specifically to modeling filament spool **42** and modeling spindle **43**. Spindle **43** extends horizontally from drybox **45** and has a semi-circular shape. A semi-circular connector **174** having a set of six depressible connector pins **176** is mounted on top of spindle **43** adjoining drybox **45**. A spring-loaded latch **178** is embedded in the top of spindle **43** at an outer edge **179**.

Filament spool **42** is comprised of a center barrel **180** on which filament may be wound, a pair of spool flanges **181** extending from either end of barrel **180**, a sleeve **182** that fits within barrel **180** for receiving spindle **43**, and modeling EEPROM board **120** mounted inside sleeve **182** and perpendicular to barrel **180**. Barrel **180** rotates about sleeve **182** so that filament **40** may be unwound from spool **42**. Sleeve **182** has a flange **184** at one end, a flange **186** at the opposite end, and an interior semi-circular cavity for receiving spindle **43**. In the preferred embodiment, flange **184** is removable and flange **186** is fixed. Removal of flange **184** allows withdrawal of sleeve **182** from barrel **180**. As mentioned above, EEPROM board **120** carries EEPROM **188**. In a preferred embodiment, EEPROM board **120** is mounted adjacent fixed flange **186** by a pair of screws **190**, so that EEPROM **188** faces inward towards sleeve **182** for protection. EEPROM board **120** on its outward facing side carries a set of six round electrical contacts **192**, as shown in FIG. 7A. Connectors **192** are configured so as to provide a receiving surface for connector pins **176** when spool **42** is mounted on spindle **43**.

Latch **178** must be manually depressed to allow insertion or removal of spindle **43** from sleeve **182**. When sleeve **182** is mounted on spindle **43**, latch **179** rests in an upward position so as to lock spool **42** into place such that contacts **192** fully depress connector pins **176**. When filament spool **42** is manually inserted onto spool holder **43**, electrical contact between EEPROM board **120** and drybox processor board **116** is made through the connector **190**.

Detail of the extrusion apparatus is shown in FIG. **8**. While FIG. **8** shows modeling extrusion apparatus **30**, it should be understood that support extrusion apparatus **44** contains the same parts and operates in the same manner as modeling extrusion apparatus **30**, at a 180° rotation. Extrusion head **32** is mounted below x-y forcer **38** by a pair of mounting plates **200**. Two pairs of bolts **202** attach head **32** to plates **200**. Two bolts **204** connect plates **200** to x-y forcer **38** to hold head **32**.

Extrusion head **32** is formed of an enclosure **206** which holds liquifier **59**, a filament drive **208** and safety switch **210**. Liquifier **59** comprises a thermal conducting thin-wall tube **212**, a heating block **214**, an extrusion tip **216**, a tip retainer **218**, heater **220** and thermocouple **222**. FIG. **9** shows liquifier **59** in an exploded view. As shown in FIG. **9**, thin-wall tube **212** has an inlet end **224**, an outlet end **226**, and is bent at a 90° angle. In the preferred embodiment, tip **216** is soldered into the outlet end of tube **212**. Alternatively, tip **216** may be brazed or welded to tube **212**. Using a 0.070 inch filament, tube **212** preferably has an inner diameter of about 0.074 inches. The wall thickness of tube **212** is preferably between 0.005–0.015 inches. It is desirable to keep tube **212** as thin as possible to achieve maximum heat transfer across tube **212** to filament **40**. In the preferred embodiment, tube **212** is made of stainless steel. Other metals may also be used, such as brass, copper, tungsten, titanium, molybdenum, beryllium copper or other steels. Other thermal conducting materials such as polymide (Kapton), a plastic with a high melting temperature, may also be used to form the thin-wall tube.

Tube **212** fits into a channel **229** of heating block **214**, between a front section **228** and a rear section **230** of the heating block. Heating block **214** is made of a heat conductive material such as aluminum or beryllium copper. A set of four bolts **232** extend through outer section **228** and rear section **230** of heating block **214** to hold tube **212**. When mounted in heating block **214**, a first section of tube **212** adjacent the inlet end **224** is exterior to heating block **214**, and a second .mid-section of tube **212** is clamped within heating block **214**, and a third section of tube **212** including tip **216** extends through the bottom of block **214**. The first section of tube **212** forms a cap zone for the liquifier **59**, the second section of tube **212** forms a heating zone, and the third section forms a nozzle zone. The nozzle zone is contained within and silver soldered to extrusion tip **216**, which is supported against heating block **214** by tip retainer **218**, a square plate having a center orifice. Tip retainer **218** is press fit around the extrusion tip **216**, and mounted beneath heating block **214** by a pair of screws **234**.

The length of the cap zone of tube **212** is in the range of 0.15 inches and 2 inches. The cap zone must undergo a temperature gradient from about 70 degrees C. envelope temperature to about 280 degrees C. liquifier temperature. A shorter cap zone allows for greater control by the system over the rate that molten filament is extruded (i.e., flow rate), but makes it more difficult to maintain a cool temperature for the filament through the cap zone. The length of the heating zone is anywhere from 0.04 inches to 7 inches. The longer the heating zone, the higher the maximum extruded flow rate, but the slower that the flow rate can be accelerated and decelerated. A liquifier having a cap zone of between 0.02–0.04 inches long and a heating zone of about 2.5 inches long has been successfully used in a preferred embodiment of the system.

Cylindrical heater **220** and thermocouple **222** extend horizontally into rear section **230** of heating block **214**. Heater **220** is positioned in heat exchange relation to the heating zone of tube **212**, to heat the tube to a temperature just above the melting temperature of the filament. Using an ABS composition for the filament **40**, the tube is heated to about 270 degrees C. Thermocouple **222** is positioned adjacent tube **212** to monitor the temperature in the tube. Safety switch **210** will cause the system **10** to shut down if temperature exceeds a predetermined level.

A guide tube **236** guides filament **40** from pivot **36** to extrusion head **32**, made of a suitable low friction material such as Teflon for support in motion. As described above, filament **40** within guide tube **36** are located within flexible tube **60** contained inside of arm **34**. Filament **40** enters extrusion head **32** through an inlet aperture **238**. Inside of extrusion head **32**, filament **40** is fed through a tapered guide **240** having a restricted guide passage **242**. Filament drive **208**, comprised of a stepper motor **246**, a pully **248** and a pair of feed rollers **250** and **252**. Roller **250** has a drive shaft **254** which is driven by stepper motor **246**. Roller **252** is a rubber-coated idler. Filament **40** is fed from the guide passage **242** of tapered guide **240** into a nip between rollers **250** and **252**. The rotation of roller **250** advances filament **40** towards liquifier **59**. The inlet end **224** of thin-wall tube **212** is positioned to receive filament **40** as it passes through rollers **250** and **252**. The flow rate of the molten filament out of liquifier **59** is controlled by the speed at which filament drive **208** advances the filament **40** into liquifier **59**.

A blower **256** blows air at ambient temperature into flexible tube **60** to cool guide tube **236** and filament **40**. Cooling of strand **40** is important so as to maintain the filament at a sufficiently low temperature that is does not become limp and buckled within the passages leading into the liquifier **59**. Air from blower **256** travels through tube **60** and enters extrusion head **32** via an air conduit **258**. Air conduit **258** provides a path for the air which is in a forward and parallel position from filament **40** within extrusion head **32**.

FIGS. **10**A and **10**B show an alternative embodiment of the liquifier. FIG. **10**A shows liquifier **259** in an assembled view, while **10**B shows liquifier **259** in an exploded view. In this embodiment, two thin-wall tubes **260**A and **260**B of the type described above flow into one, nozzle **262**. A liquifier of this type can be substituted into the dispensing head shown in FIG. **8** to provide one extrusion head that dispenses, at alternate times, two different deposition materials. The two deposition materials may be a modeling and a supply material, or they may be modeling materials of two different colors or having other diverse properties. Nozzle **262** is brazed or welded to the outlet ends **264** of tubes **260**A and **260**B. Nozzle **262** is positioned in a vertical orientation, while tubes **260**A and **260**B may be angled towards the horizontal. Separate feed mechanisms (not shown) are provided for tubes **260**A and **260**B so that filament material is fed into only one of the tubes at any given time.

Thin-wall tubes **260**A and **260**B are held into position by a heating block **266**. Heating block **266** is comprised of an outer plate **268**, an interior plate **270** and a rear plate **272**. Rear plate **272** is mounted within the extrusion head, and holds a heater **274** which extends between tubes **260**. Two channels **276** which hold tubes **260**A and **260**B are routed through interior block **270**. A set of five bolts (not shown) extend through outer plate **268**, interior plate **270** and rear plate **272** to detachably hold together liquifier **259**. It is an advantageous that the liquifier be removable from the heating block, for replacement and cleaning.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

We claim:

1. An extrusion head for depositing layers of solidifying material in a desired pattern to form three-dimensional physical objects, the extrusion head comprising:

a heating block made of heat conductive material;

a heating element to heat the heating block;

a first thin-wall tube having an inlet end for receiving a filament of a first material, an outlet end for delivering the first material in a molten state, and having a first section adjacent the inlet end and exterior to the heating block and a second section which passes through the heating block;

a material advancee mechanism positioned to advance the filament of first material into the inlet end of the first thin-wall tube; and

a nozzle at the outlet end of the first thin-wall tube for dispensing the first material in a molten state.

2. The extrusion head of claim 1 wherein:

the heating element is within the heating block and is in heat exchange relation to the second section of the first thin-wall tube.

3. The extrusion head of claim 2 wherein:

the heating block is comprised of a first and a second section, which are mechanically detachable to allow removal of the first thin-wall tube.

4. The extrusion head of claims 1, 2 or 3 wherein:

the first thin-wall tube is made of metal.

5. The extrusion head of claim 4 wherein:

the nozzle is swaged into the outlet of the first thin-wall tube.

6. The extrusion head of claim 4 wherein:

the first thin-wall tube is made of stainless steel.

7. The extrusion head of claim 6 wherein:

the filament of first material has a diameter of about 1/16th inches; and

the first thin-wall tube has a wall thickness in the range of 0.008–0.015 inches, and an interior diameter of about 0.07 inches.

8. The extrusion head of claim 7 wherein:

the nozzle is swaged into the outlet end of the first thin-wall tube.

9. The extrusion head of claim 7 wherein:

the first section of the first tube is in the range of 0.02–0.04 inches long, and the second section of the first tube is about 2.5 inches long.

10. The extrusion head of claim 1 and further comprising:

a second thin-wall tube having an inlet end for receiving a filament of a second material, an outlet end for delivering the second material in a molten state, and having a first section adjacent the inlet end and exterior to the heating block and a second section which passes through the heating block;

a second material advance mechanism positoned to advance the filament of second material into the inlet end of the second tube; and

wherein the nozzle has a first entrance for receiving the first material, a second entrance for receiving the second material from the outlet end of the second tube, and angle exit for dispensing the first and second materials, at separate times, in molten states.

11. The extrusion head of claim 10 wherein:

the heating element is within the heating block and is in heat exchange relation to the second sections of the first and second metal tubes.

12. The extrusion head of claim 11 wherein:

the heating block is comprised of a first, second and third sections, which are mechanically detectable to allow removal of the first and second thin-wall tubes.

13. The extrusion head of claim 10 or 11 or 12 wherein:

the first and second thin-wall tubes are made of metal.

14. The extrusion head of claims 13 wherein:

the first and second metal tubes are made of stainless steel.

15. The extrusion head of claim 14 wherein:

the filaments of first and second materials each have a diameter of about 1/16th inches; and

the first and second metal tubes each have a wall thickness in the range of 0.008–0.015 inches, and an interior diameter of about 0.07 inches.

16. The extrusion head of claim 15 wherein:

the first section of the first and second thin-wall tubes are each in the range of 0.02–0.04 inches long, and the second section of the first and second thin-wall tubes are about 2.5 inches long.

17. A liquifier for receiving a filament of material and liquefying the material for deposition in a molten state, comprising:

a heating block made of heat conductive material;

a first thin-wall tube having an inlet end for receiving a filament of a first material, an outlet end for delivering the first material in a molten state, and having a first section adjacent the inlet end and exterior to the heating block and a second section which passes through the heating block; and

a nozzle at the outlet end of the first thin-wall tube for dispensing the first material in a molten state.

18. The liquifier of claim 17 and further comprising:

a heating element within the heating block and in heat exchange relation to the second section of the first thin-wall tube.

19. The liquifier of claim 18 wherein:

the block heating is comprised of a first and a second section which are mechanically detachable to allow removal of the first thin-wall tube.

20. The liquifier of claims 17, 18 or 19 wherein:

the first thin-wall tube is made of metal.

21. The liquifier of claim 20 wherein:

the nozzle is swaged into the outlet of the first thin-wall tube.

22. The liquifier of claim 20 wherein:

the first thin-wall tube is made of stainless steel.

23. The liquifier of claim 22 wherein:

the filament of first material has a diameter of about 1/16th inches; and

the first thin-wall metal tube has a wall thickness in the range of 0.008–0.015 inches, and an interior diameter of about 0.07 inches.

24. The liquifier of claim 23 wherein:

the nozzle is swaged into the outlet end of the first metal tube.

25. The liquifier of claim 23 wherein:

the first section of the first metal tube is in the range of 0.02–0.04 inches long inches long, and the second section of the first metal tube is about 2.5 inches long.

26. The liquifier of claim **17** and further comprising:

a second thin-wall tube having an inlet end for receiving a filament of a second material, an outlet end for delivering the second material in a molten state, and having a first section adjacent the inlet end and exterior to the heating block and a second section which passes through the heating block; and

wherein the nozzle has a first entrance for receiving the first material, a second entrance for receiving the second material from the outlet end of the second tube, and a single exit for dispensing the first and second materials, at separate times, in molten states.

27. The liquifier of claim **26** and further comprising:

a heating element within the heating block and in heat exchange relation to the second sections of the first and second thin-wall tubes.

28. The liquifier head of claim **27** wherein:

the heating block is comprised of a first, second and third sections, which are mechanically detachable to allow removal of the first and second thin-wall tubes.

29. The liquifier of claim **26** or **27** or **28** wherein:

the first and second thin-wall tubes are made of metal.

30. The liquifier of claims **29** wherein:

the first and second metal tubes are made of stainless steel.

31. The liquifier of claim **30** wherein:

the filaments of first and second materials each have a diameter of about 1/16th inches; and

the first and second metal tubes each have a wall thickness in the range of 0.008–0.015 inches, and an interior diameter of about 0.07 inches.

32. The liquifier of claim **31** wherein: the first section of the first and second metal tubes are each in the range of 0.02–0.04 inches long, and the second section of the first and second metal tubes are each about 2.5 inches long.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,004,124
DATED : DECEMBER 21, 1999
INVENTOR(S) : WILLIAM J. SWANSON ET AL.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Col. 5, line 20, delete "suface", insert --surface--

Col. 7, line 33, delete "ETR", insert --HTR--

Col. 8, line 22, after "C", delete --.--

Col. 9, line 15, delete "often", insert --of ten--

Col. 11, line 50, after "C", delete --.--

Col. 13, line 8, delete "flament", insert --filament--

Col. 13, line 59, delete "angle", insert --single--

Col. 14, line 42, delete "block heating", insert --heating block--

Signed and Sealed this

Twenty-eighth Day of November, 2000

Attest:

Q. TODD DICKINSON

Attesting Officer *Director of Patents and Trademarks*

EXHIBIT D

US008349239B2

(12) **United States Patent**
Hopkins et al.

(10) **Patent No.: US 8,349,239 B2**
(45) **Date of Patent: Jan. 8, 2013**

(54) **SEAM CONCEALMENT FOR THREE-DIMENSIONAL MODELS**

(75) Inventors: **Paul E. Hopkins**, Savage, MN (US); **Donald J. Holzwarth**, Minnetonka, MN (US)

(73) Assignee: **Stratasys, Inc.**, Eden Prairie, MN (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 523 days.

(21) Appl. No.: **12/565,397**

(22) Filed: **Sep. 23, 2009**

(65) **Prior Publication Data**

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(51) **Int. Cl.**
B29C 41/02 (2006.01)
G06F 19/00 (2011.01)

(52) **U.S. Cl.** **264/308**; 700/119

(58) **Field of Classification Search** 264/308; 700/119

See application file for complete search history.

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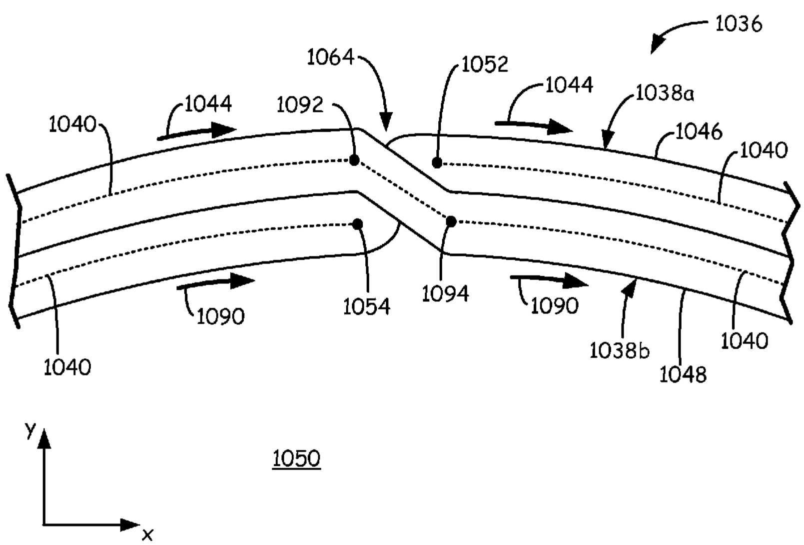
Primary Examiner — Leo B Tentoni

(74) *Attorney, Agent, or Firm* — Brian R. Morrison; Westman, Champlin & Kelly, P.A.

(57) **ABSTRACT**

A three-dimensional model built with an extrusion-based digital manufacturing system, and having a perimeter based on a contour tool path that defines an interior region of a layer of the three-dimensional model, where at least one of a start point and a stop point of the contour tool path is located within the interior region of the layer.

18 Claims, 9 Drawing Sheets



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MB060

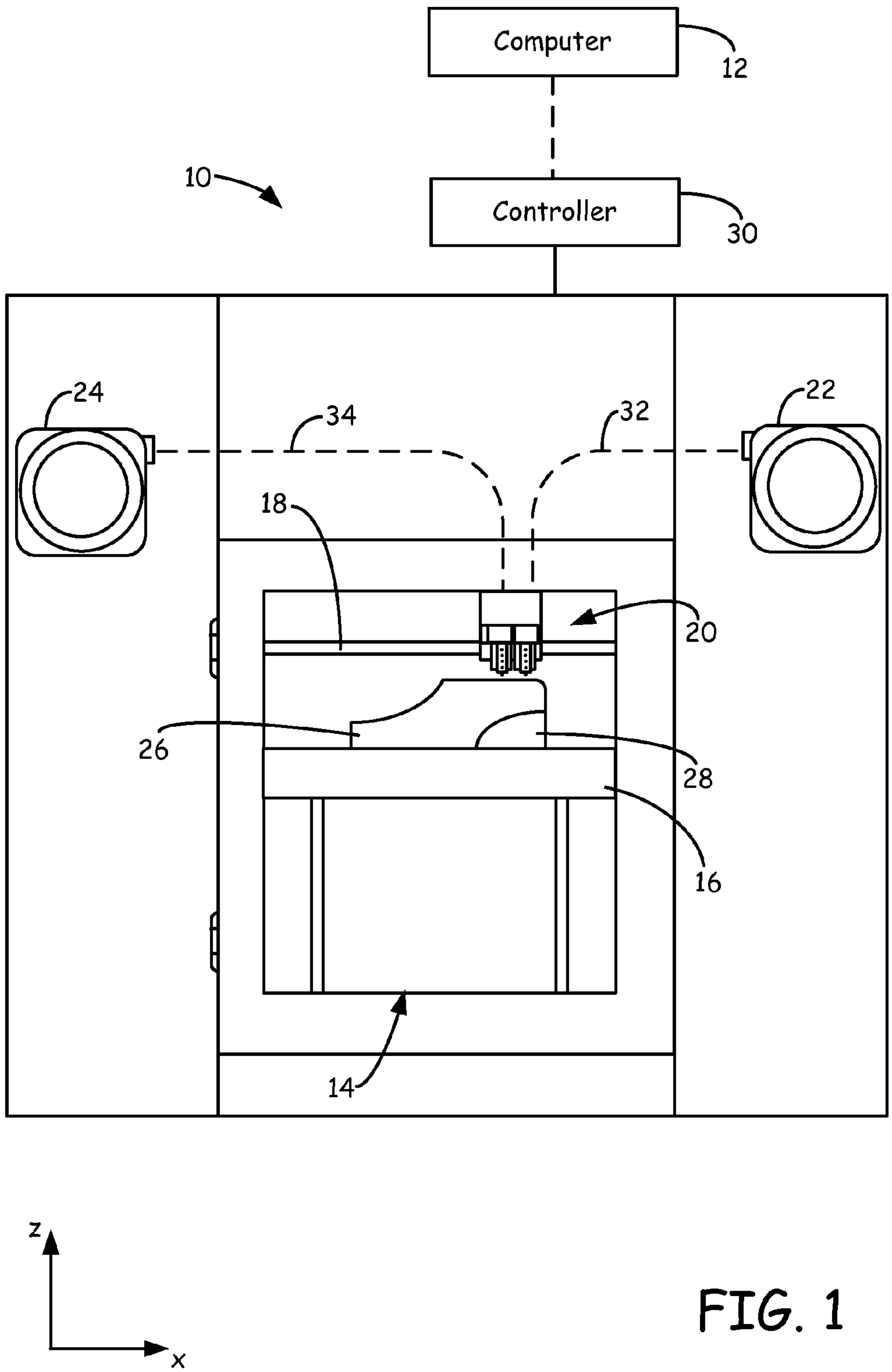

FIG. 1

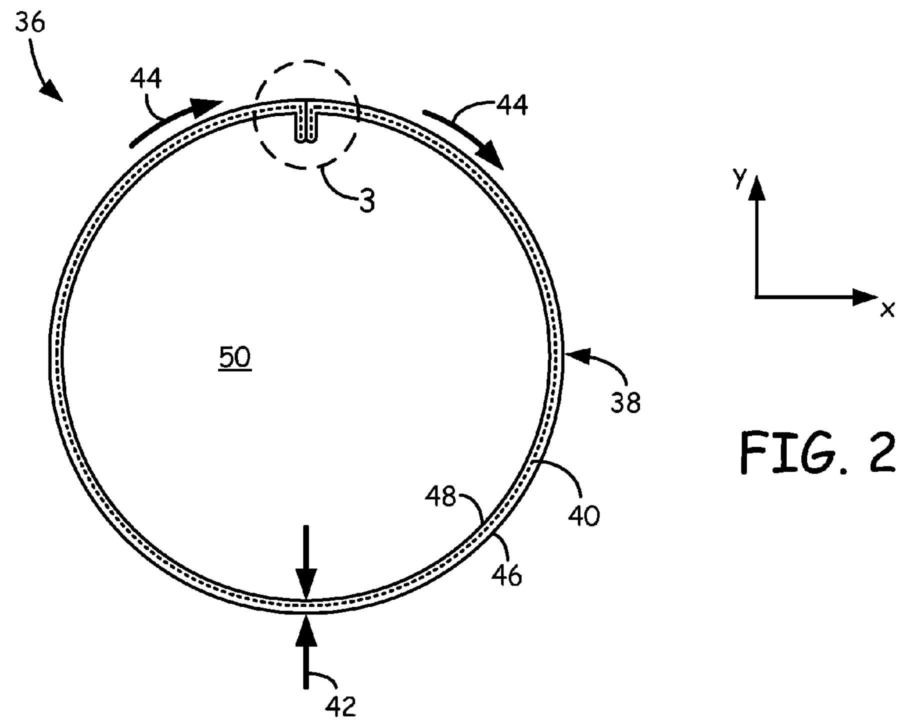
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FIG. 2

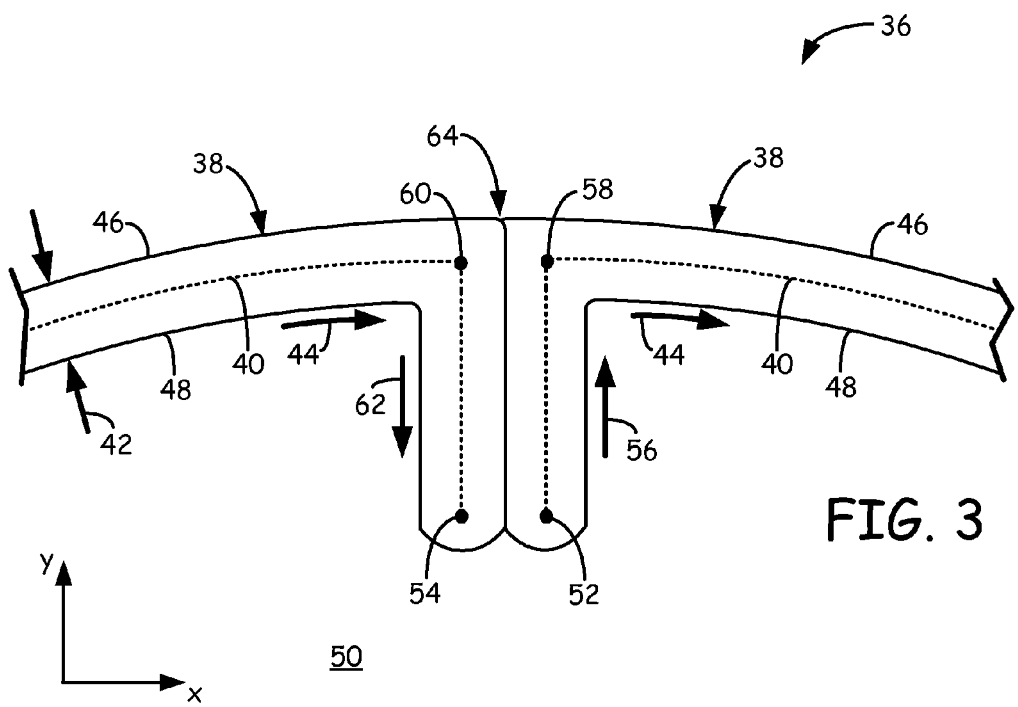
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FIG. 3

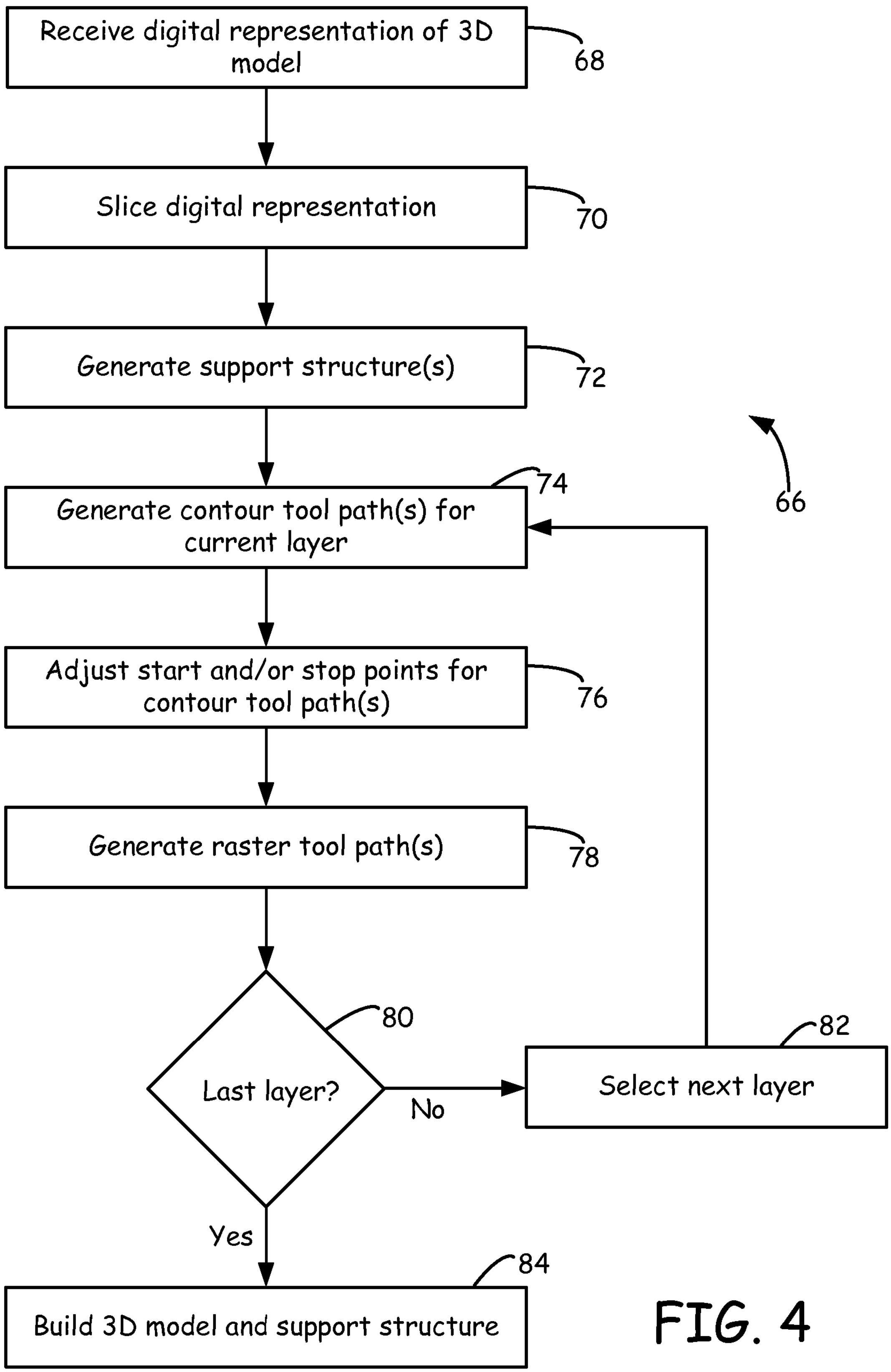
Receive digital representation of 3D model
68
Slice digital representation
70
Generate support structure(s)
72
74
66
Generate contour tool path(s) for current layer
Adjust start and/or stop points for contour tool path(s)
76
Generate raster tool path(s)
78
80
82
Last layer?
No
Select next layer
Yes
84
Build 3D model and support structure

FIG. 4

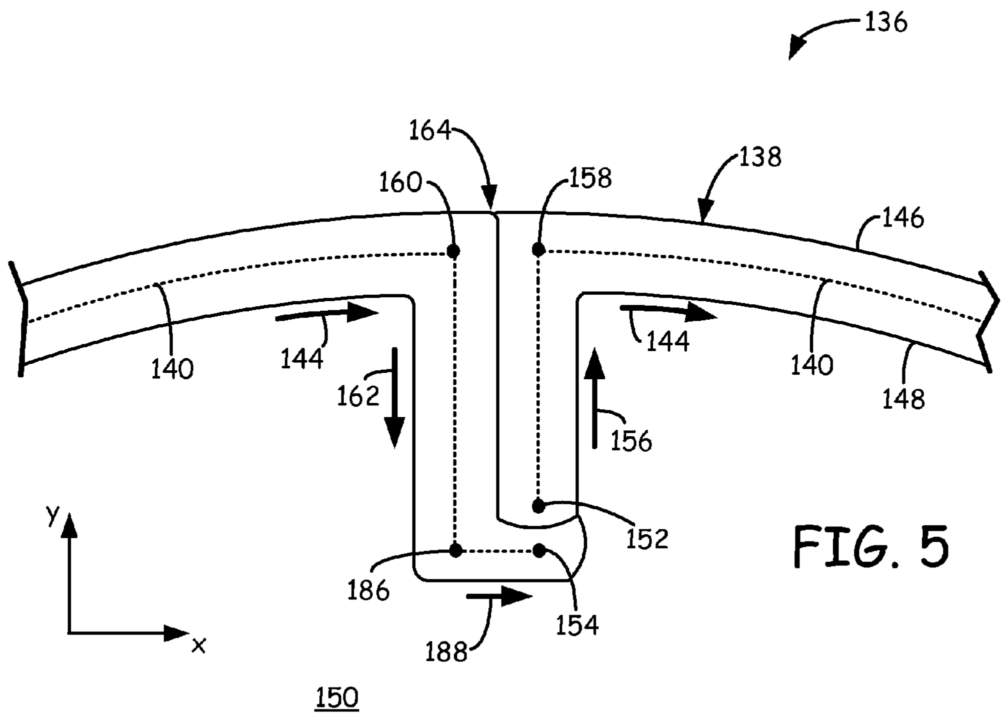
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FIG. 5

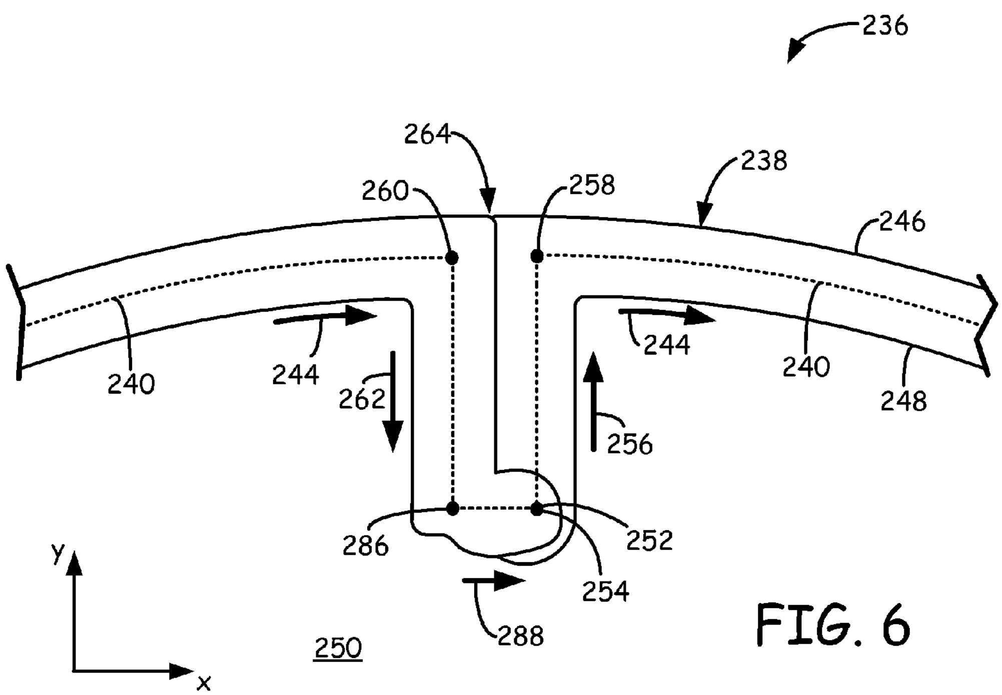
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FIG. 6

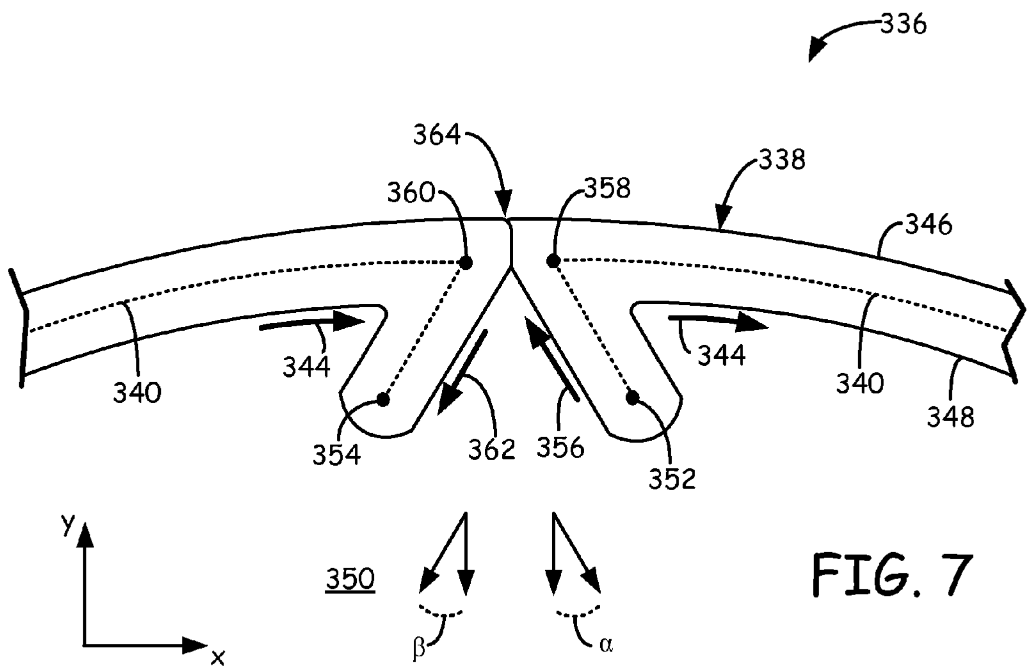
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FIG. 7

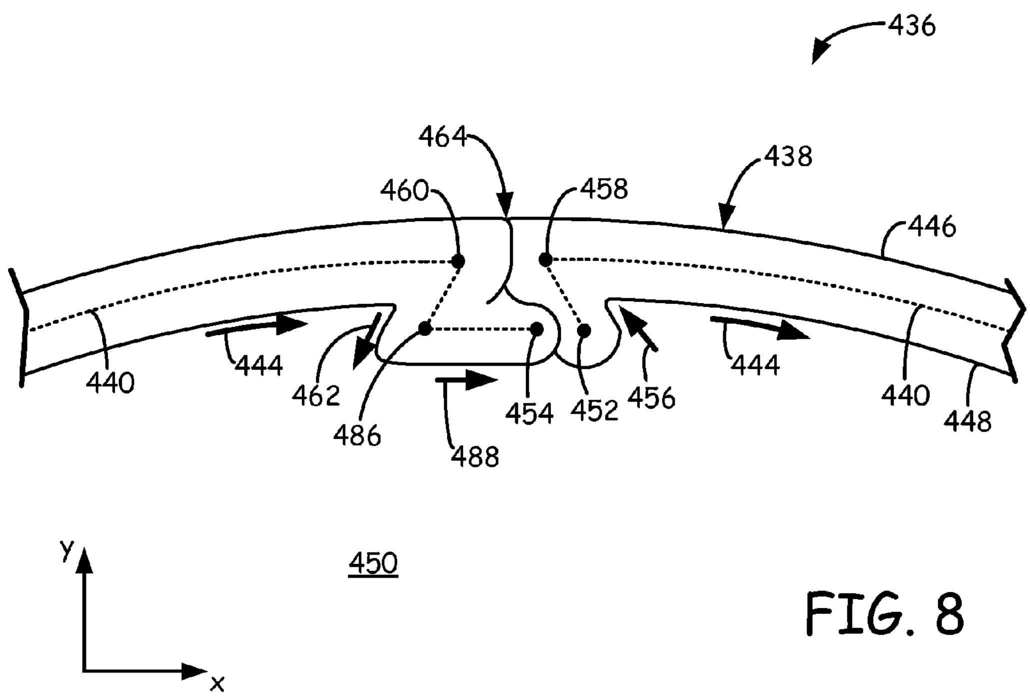
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FIG. 8

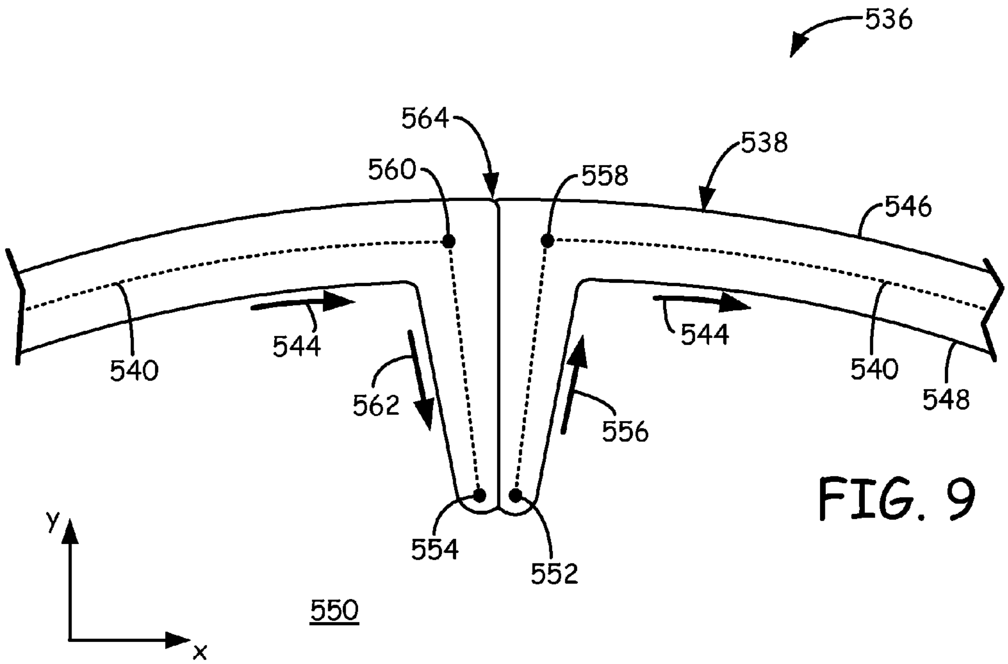
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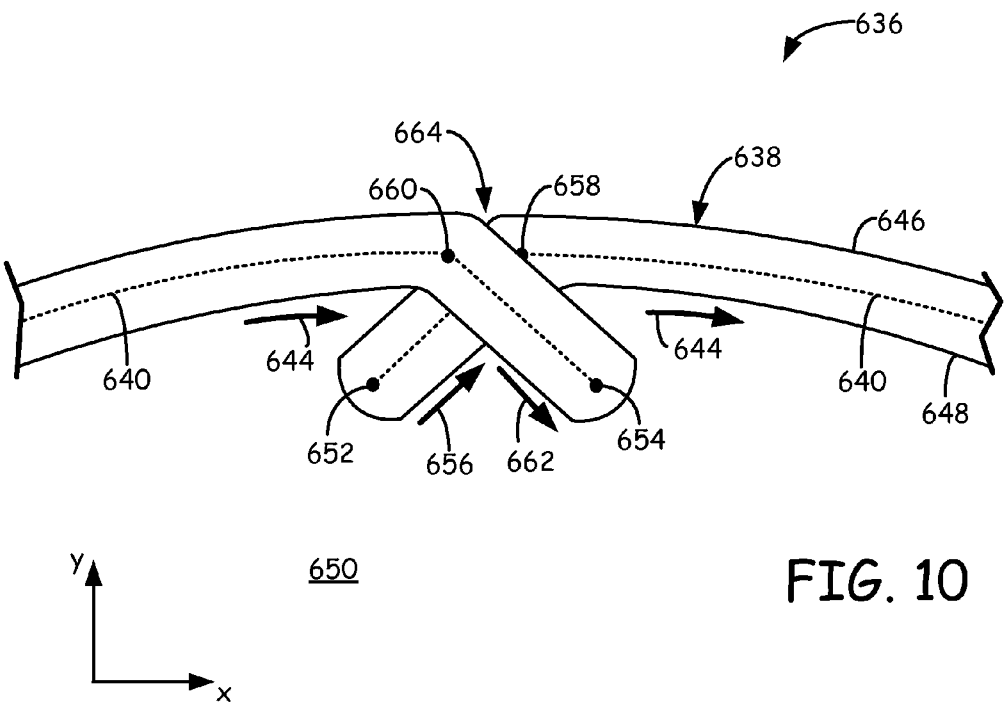
FIG. 9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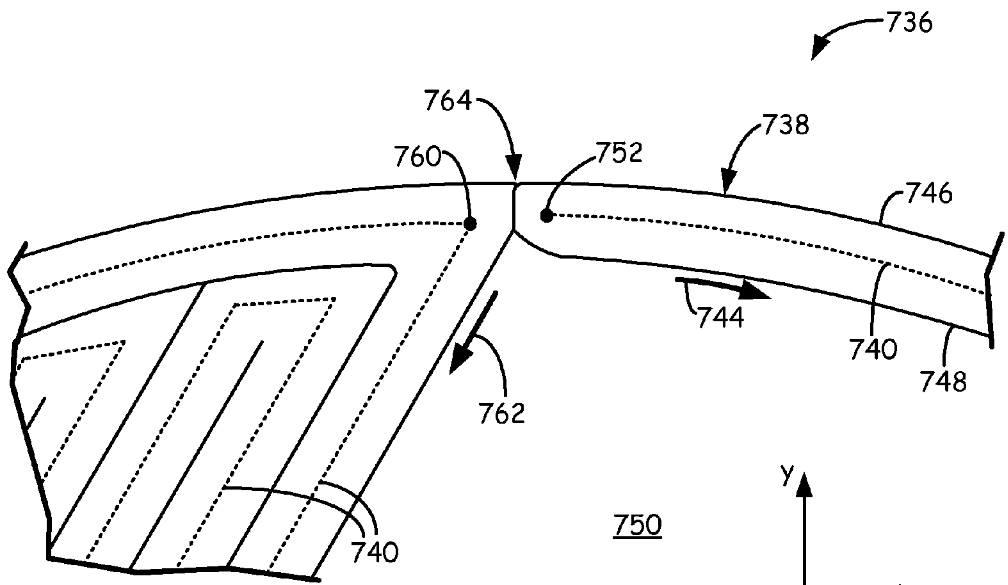
x
650

FIG. 10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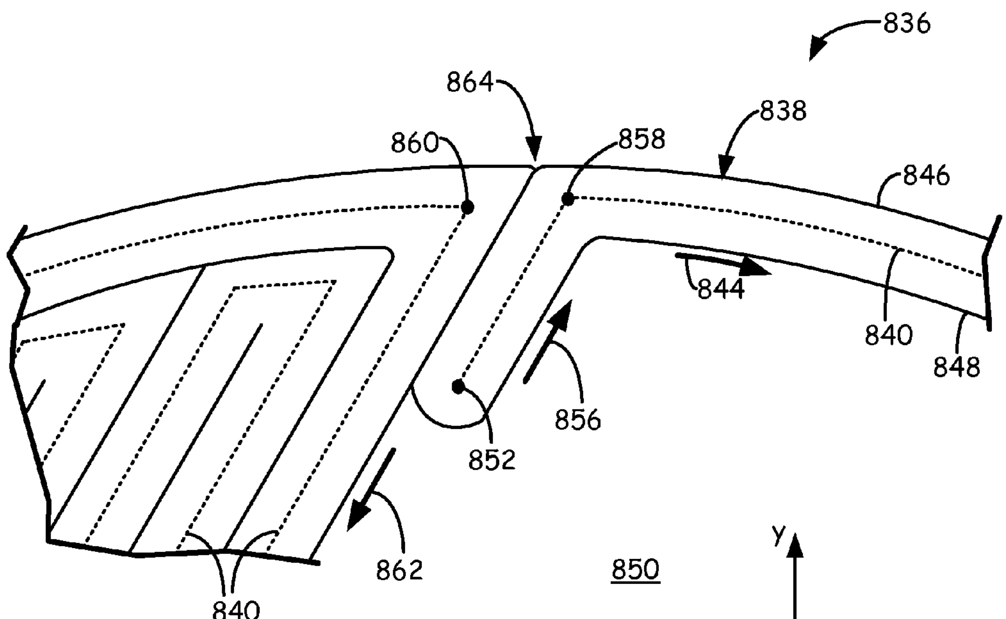
Y
X
740

FIG. 11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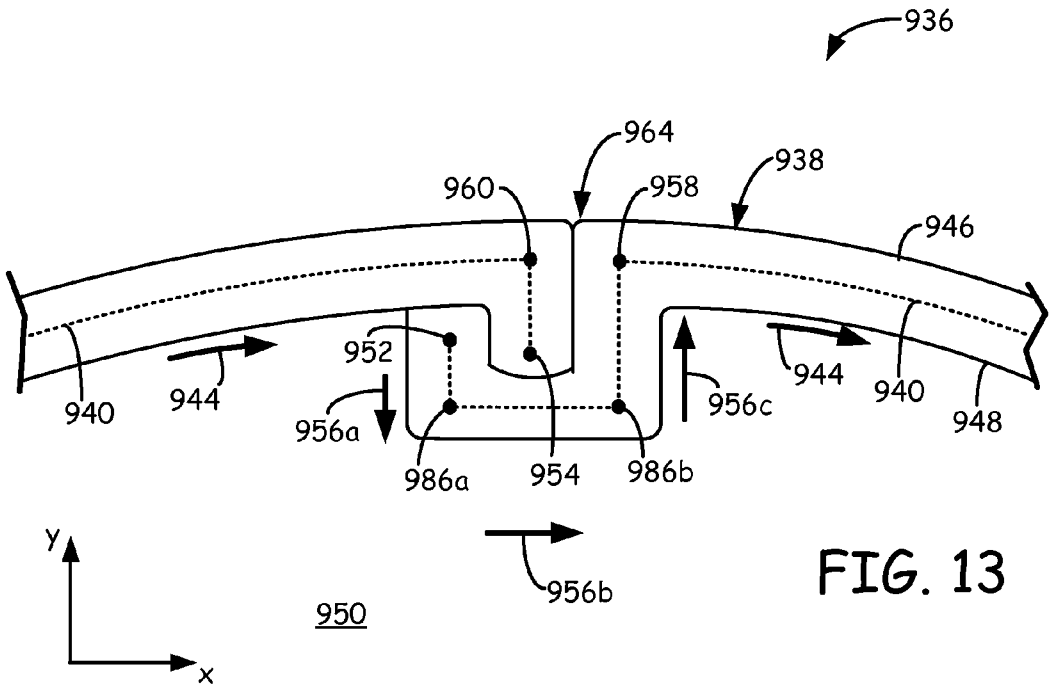
X
840

FIG. 12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946
952
944
940
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944
940
944
948
956a
986a
954
986b
y
956b
950
x

FIG. 13

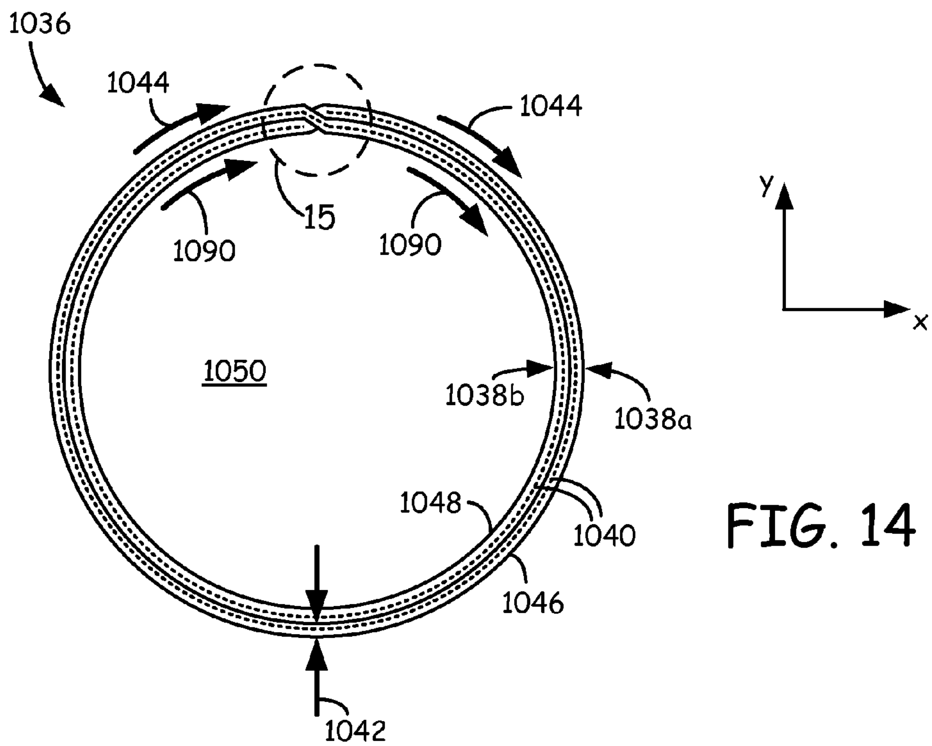

1036
1044
1044
15
1090
1090
y
x
1050
1038b
1038a
1048
1040
1046
1042

FIG. 14

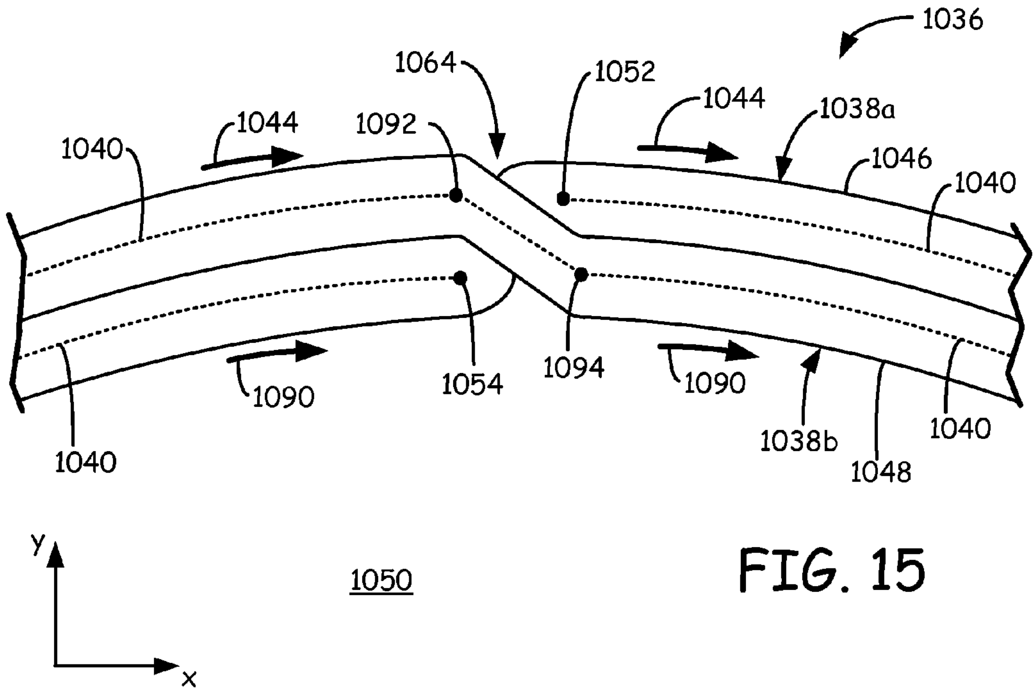

1036
1064
1052
1044
1038a
1044
1092
1046
1040
1040
1040
1090
1054
1094
1090
1038b
1040
1040
1048
y
x
1050

FIG. 15

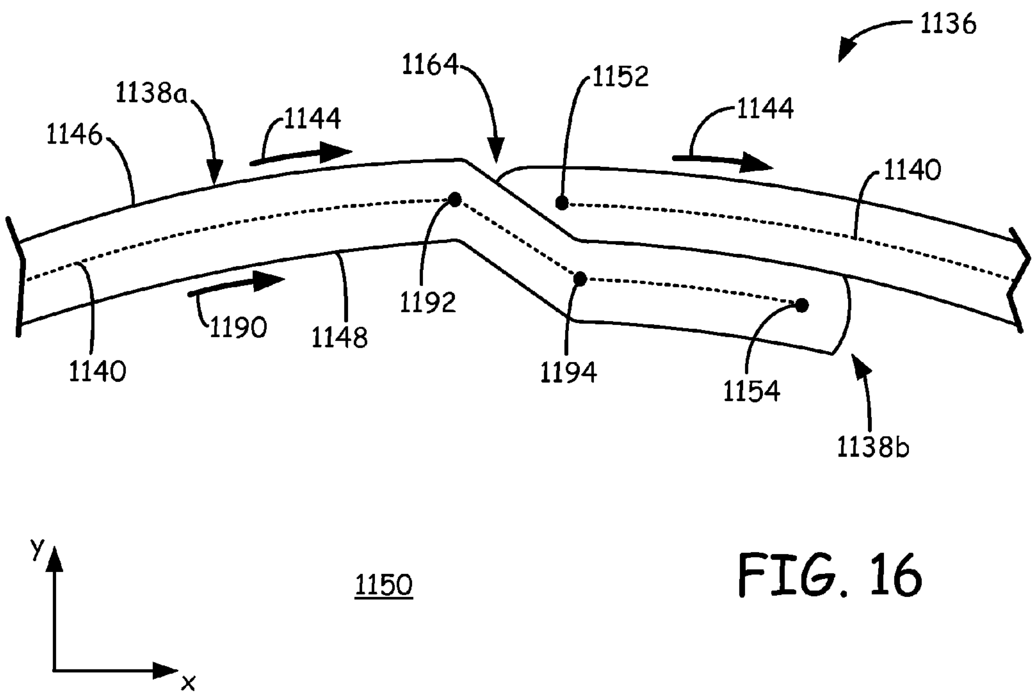

1136
1164
1152
1138a
1144
1144
1146
1140
1190
1148
1192
1194
1154
1140
1138b
y
x
1150

FIG. 16

SEAM CONCEALMENT FOR THREE-DIMENSIONAL MODELS

BACKGROUND

The present disclosure relates to direct digital manufacturing systems for building three-dimensional (3D) models. In particular, the present invention relates to techniques for building 3D models with extrusion-based digital manufacturing systems.

An extrusion-based digital manufacturing system (e.g., fused deposition modeling systems developed by Stratasys, Inc., Eden Prairie, Minn.) is used to build a 3D model from a digital representation of the 3D model in a layer-by-layer manner by extruding a flowable consumable modeling material. The modeling material is extruded through an extrusion tip carried by an extrusion head, and is deposited as a sequence of roads on a substrate in an x-y plane. The extruded modeling material fuses to previously deposited modeling material, and solidifies upon a drop in temperature. The position of the extrusion head relative to the substrate is then incremented along a z-axis (perpendicular to the x-y plane), and the process is then repeated to form a 3D model resembling the digital representation.

Movement of the extrusion head with respect to the substrate is performed under computer control, in accordance with build data that represents the 3D model. The build data is obtained by initially slicing the digital representation of the 3D model into multiple horizontally sliced layers. Then, for each sliced layer, the host computer generates one or more tool paths for depositing roads of modeling material to form the 3D model.

In fabricating 3D models by depositing layers of a modeling material, supporting layers or structures are typically built underneath overhanging portions or in cavities of objects under construction, which are not supported by the modeling material itself. A support structure may be built utilizing the same deposition techniques by which the modeling material is deposited. The host computer generates additional geometry acting as a support structure for the overhanging or free-space segments of the 3D model being formed. Consumable support material is then deposited from a second nozzle pursuant to the generated geometry during the build process. The support material adheres to the modeling material during fabrication, and is removable from the completed 3D model when the build process is complete.

SUMMARY

A first aspect of the present disclosure is directed to a method for building a 3D model with an extrusion-based digital manufacturing system. The method includes generating a contour tool path that defines an interior region of a layer of the 3D model, where the contour tool path comprises a start point and a stop point, and where at least one of the start point and the stop point is located within the interior region of the layer.

Another aspect of the present disclosure is directed to a method for building a 3D model with an extrusion-based digital manufacturing system, where the method includes receiving data comprising tool paths for building a plurality of layers of the 3D model. The method also includes extruding a material in a pattern based on the tool paths to form a perimeter of the extruded material for one of the layers of the 3D model, where the perimeter has a start point and a stop point, and defines an interior region of the layer, and where at least one of the start point and the stop point is located within the interior region of the layer.

Another aspect of the present disclosure is directed to a 3D model built with an extrusion-based digital manufacturing system. The 3D model includes a plurality of layers of an extruded material, where at least one of the layers includes a perimeter of the extruded material, and where the perimeter has a start point and a stop point. The layer also includes an interior region defined by the perimeter, where at least one of the start point and the stop point is located within the interior region of the layer.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a front view of an extrusion-based digital manufacturing system for building 3D models and support structures.

FIG. **2** is a top view of a layer of a 3D model being built with the extrusion-based digital manufacturing system.

FIG. **3** is an expanded view of section 3 taken in FIG. **2**, illustrating a seam of the layer with an open-square arrangement.

FIG. **4** is a flow diagram of a method for generating data and building a 3D model having concealed seams.

FIG. **5** is an alternative expanded view of section 3 taken in FIG. **2**, illustrating a seam of a first alternative layer with a closed-square arrangement.

FIG. **6** is an alternative expanded view of section 3 taken in FIG. **2**, illustrating a seam of a second alternative layer with an overlapped closed-square arrangement.

FIG. **7** is an alternative expanded view of section 3 taken in FIG. **2**, illustrating a seam of a third alternative layer with an open-triangle arrangement.

FIG. **8** is an alternative expanded view of section 3 taken in FIG. **2**, illustrating a seam of a fourth alternative layer with a closed-triangle arrangement.

FIG. **9** is an alternative expanded view of section 3 taken in FIG. **2**, illustrating a seam of a fifth alternative layer with a converging-point arrangement.

FIG. **10** is an alternative expanded view of section 3 taken in FIG. **2**, illustrating a seam of a sixth alternative layer with an overlapped-cross arrangement.

FIG. **11** is an alternative expanded view of section 3 taken in FIG. **2**, illustrating a seam of a seventh alternative layer with a combined perimeter and raster pattern arrangement, where a start point is located adjacent to the seam and a stop point is located within an interior region.

FIG. 12 is an alternative expanded view of section 3 taken in FIG. **2**, illustrating a seam of an eighth alternative layer with a combined perimeter and raster pattern arrangement, where start and stop points are each located within an interior region.

FIG. **13** is an alternative expanded view of section 3 taken in FIG. **2**, illustrating a seam of a ninth alternative layer with an crimped-square arrangement.

FIG. **14** is a top view of a tenth alternative layer of the 3D model being built with the extrusion-based digital manufacturing system.

FIG. **15** is an expanded view of section 15 taken in FIG. **14**, illustrating a seam of the tenth alternative layer with a step-over arrangement.

FIG. **16** is an alternative expanded view of section 15 taken in FIG. **14**, illustrating a seam of an eleventh alternative layer with a shortened step-over arrangement.

DETAILED DESCRIPTION

The present disclosure is directed to a method for building 3D models with deposition patterns that contain concealed seams. As discussed below, the method involves adjusting the start point and/or the stop point of a contour tool path of a 3D model layer to one or more locations that are within an interior region of the layer. This effectively conceals the seam that is formed at the intersection of the starting and stop points, which can increase the aesthetic and functional qualities of the resulting 3D model.

The following discussion of 3D models with concealed seams is made with reference to 3D models built with modeling materials since consumers are generally more concerned about the aesthetic and physical qualities of the intended 3D models, and are less concerned about such qualities of the "support materials" used to form support structures, which are typically removed and discarded. However, the techniques for forming concealed seams may also be used to form support structures having concealed seams. Thus, the term "three-dimensional model" may apply to a 3D model built with a modeling material and to a support structure built with a support material.

FIG. **1** is a front view of system **10** in use with computer **12**, where system **10** is an extrusion-based digital manufacturing system that may be used to build 3D models and/or support structures with concealed seams. As shown, system **10** includes build chamber **14**, platen **16**, gantry **18**, extrusion head **20**, and supply sources **22** and **24**. Suitable extrusion-based digital manufacturing systems for system **10** include fused deposition modeling systems developed by Stratasys, Inc., Eden Prairie, Minn.

Build chamber **14** is an enclosed, heatable environment that contains platen **16**, gantry **18**, and extrusion head **20** for building a 3D model (referred to as 3D model **26**) and a corresponding support structure (referred to as support structure **28**). Platen **16** is a platform on which 3D model **26** and support structure **28** are built, and moves along a vertical z-axis based on signals provided from controller **30**. As discussed below, controller **30** directs the motion of platen **16** and extrusion head **20** based on data supplied by computer **12**.

Gantry **18** is a guide rail system configured to move extrusion head **20** in a horizontal x-y plane within build chamber **14** based on signals provided from controller **30**. The horizontal x-y plane is a plane defined by an x-axis and a y-axis (not shown in FIG. **1**), where the x-axis, the y-axis, and the z-axis are orthogonal to each other. In an alternative embodiment, platen **16** may be configured to move in the horizontal x-y plane within build chamber **14**, and extrusion head **20** may be configured to move along the z-axis. Other similar arrangements may also be used such that one or both of platen **16** and extrusion head **20** are moveable relative to each other.

Extrusion head **20** is supported by gantry **18** for building 3D model **26** and support structure **28** on platen **16** in a layer-by-layer manner, based on signals provided from controller **30**. Accordingly, controller **30** also directs extrusion head **20** to selectively deposit the modeling and support materials based on data supplied by computer **12**. In the embodiment shown in FIG. **1**, extrusion head **20** is a dual-tip extrusion head configured to deposit modeling and support materials from supply source **22** and supply source **24**, respectively.

Examples of suitable extrusion heads for extrusion head **20** include those disclosed in LaBossiere, et al., U.S. Patent Application Publication Nos. 2007/0003656 and 2007/00228590; and Leavitt, U.S. Patent Application Publication No. 2009/0035405. Alternatively, system **10** may include one or more two-stage pump assemblies, such as those disclosed in Batchelder et al., U.S. Pat. No. 5,764,521; and Skubic et al., U.S. Patent Application Publication No. 2008/0213419. Furthermore, system **10** may include a plurality of extrusion heads **18** for depositing modeling and/or support materials.

The modeling material may be provided to extrusion head **20** from supply source **22** through pathway **32**. Similarly, the support material may be provided to extrusion head **20** from supply source **24** through pathway **34**. System **10** may also include additional drive mechanisms (not shown) configured to assist in feeding the modeling and support materials from supply sources **22** and **24** to extrusion head **20**.

The modeling and support materials may be provided to system **10** in a variety of different media. For example, the modeling and support materials may be provided as continuous filaments fed respectively from supply sources **22** and **24**, as disclosed in Swanson et al., U.S. Pat. No. 6,923,634; Comb et al., U.S. Pat. No. 7,122,246; and Taatjes et al, U.S. Patent Application Publication Nos. 2010/0096489 and 2010/0096485. Examples of suitable average diameters for the filaments of the modeling and support materials range from about 1.27 millimeters (about 0.050 inches) to about 2.54 millimeters (about 0.100 inches), with particularly suitable average diameters ranging from about 1.65 millimeters (about 0.065 inches) to about 1.91 millimeters (about 0.075 inches). Alternatively, the modeling and support materials may be provided as other forms of media (e.g., pellets and resins) from other types of storage and delivery components (e.g., supply hoppers and vessels).

Suitable modeling materials for building 3D model **26** include materials having amorphous properties, such as thermoplastic materials, amorphous metallic materials, and combinations thereof. Examples of suitable thermoplastic materials for ribbon filament **34** include acrylonitrile-butadiene-styrene (ABS) copolymers, polycarbonates, polysulfones, polyethersulfones, polyphenylsulfones, polyetherimides, amorphous polyamides, modified variations thereof (e.g., ABS-M30 copolymers), polystyrene, and blends thereof. Examples of suitable amorphous metallic materials include those disclosed in U.S. patent application Ser. No. 12/417,740.

Suitable support materials for building support structure **28** include materials having amorphous properties (e.g., thermoplastic materials) and that are desirably removable from the corresponding modeling materials after 3D model **24** and support structure **26** are built. Examples of suitable support materials for ribbon filament **34** include water-soluble support materials commercially available under the trade designations "WATERWORKS" and "SOLUBLE SUPPORTS" from Stratasys, Inc., Eden Prairie, Minn.; break-away support materials commercially available under the trade designation "BASS" from Stratasys, Inc., Eden Prairie, Minn., and those disclosed in Crump et al., U.S. Pat. No. 5,503,785; Lombardi et al., U.S. Pat. Nos. 6,070,107 and 6,228,923; Priedeman et al., U.S. Pat. No. 6,790,403; and Hopkins et al., U.S. Patent Application Publication No. 2010/0096072.

Prior to a build operation, computer **12** may receive a digital representation of 3D model **26**. Computer **12** is one or more computer-based systems that communicates with system **10** (e.g., with controller **30**), and may be separate from system **10**, or alternatively may be an internal component of system **10**. Upon receipt of the digital representation of 3D model **26**, computer **12** may reorient the digital representation and generate one or more supports for any overhanging regions that require vertical support (e.g., with support structure **28**).

Computer **12** may then slice the digital representation and generated supports into multiple layers. For each layer, computer **12** may then generate one or more tool paths for extrusion head **20** to follow for building each layer of 3D model **26** and support structure **28**. The generation of the tool path(s) for a layer of 3D model **26** may initially involve generating one or more contour tool paths that define the perimeter(s) of 3D model **26** for the given layer. As discussed below, computer **12** also desirably adjusts the start point and/or the stop point of each contour tool path of the layer to one or more locations that are within an interior region of the layer defined by the respective contour tool path. This effectively conceals the seam that is formed at the intersection of the start and stop points.

Based on each generated contour tool path, computer **12** may then generate one or more additional tool paths (e.g., raster paths) to fill in the interior region(s) defined by the perimeter(s), as necessary. As further discussed below, the generation of the additional tool path(s) (e.g., raster paths) desirably compensate for the adjustments in the locations of the start points and/or the stop points of the contour tool path(s).

One or more tool paths for the layer of support structure **28** may also be generated in the same manner. This process may then repeated be for each sliced layer of the digital representation, and the generated data may be stored on any suitable computer storage medium (e.g., on a storage device of computer **12**). The generated data may also be transmitted from computer **12** to controller **30** for building 3D model **26** and support structure **28**.

During a build operation, controller **30** directs one or more drive mechanisms (not shown) to intermittently feed the modeling and support materials to extrusion head **20** from supply sources **22** and **24**. For each layer, controller **30** then directs gantry **18** to move extrusion head **20** around in the horizontal x-y plane within build chamber **14** based on the generated tool paths. The received modeling and support materials are then deposited onto platen **16** to build the layer of 3D model **26** and support structure **28** using the layer-based additive technique.

The formation of each layer of 3D model **26** and support structure **28** may be performed in an intermittent manner in which the modeling material may initially be deposited to form the layer of 3D model **26**. Extrusion head **20** may then be toggled to deposit the support material to form the layer of support structure **28**. The reciprocating order of modeling and support materials may alternatively be used. The deposition process may then be performed for each successive layer to build 3D model **26** and support structure **28**. Support structure **28** is desirably deposited to provide vertical support along the z-axis for overhanging regions of the layers of 3D model **26**. After the build operation is complete, the resulting 3D model **26**/support structure **28** may be removed from build chamber **14**, and support structure **28** may be removed from 3D model **26**.

FIGS. **2** and **3** illustrate layer **36**, which is a layer of 3D model **26** formed by depositing a modeling material with system **10**. As shown in FIG. **2**, layer **36** includes perimeter path **38**, which is a road of a modeling material that is deposited by extrusion head **20** along contour tool path **40**. As discussed above, contour tool path **40** may be generated by computer **12** based on road width **42**, which is a predicted width of a deposited road of the modeling material, and may depend on a variety of factors, such as modeling material properties, the type of extrusion-based digital manufacturing system used, extrusion conditions, extrusion tip dimensions, and the like. Suitable widths for road width **42** range from about 250 micrometers (about 10 mils) to about 1,020 micrometers (about 40 mils), with particularly suitable widths ranging from about 380 micrometers (about 15 mils) to about 760 micrometers (about 30 mils).

In the current example, the modeling material is deposited along contour tool path **40** in a clockwise direction, as represented by arrows **44**, to form perimeter path **38**. Alternatively, the modeling material may be along contour tool path **40** in a counter-clockwise direction. Perimeter path **38** includes exterior surface **46** and interior surface **48**, which are each offset from contour tool path **40** by about one-half of road width **42**. Exterior surface **46** is the outward-facing surface of perimeter path **38** and may be observable when 3D model **26** is completed. Interior surface **48** is the inward-facing surface of perimeter path **38**, which defines interior region **50**. Interior region **50** is the region of layer **36** confined within perimeter path **38**, and may be filled with additional modeling material deposited along additionally generated tool paths (e.g., raster paths, not shown).

As shown in FIG. **3**, contour tool path **40** includes start point **52** and stop point **54**, where start point **52** is a first location in the x-y plane at which extrusion head **20** is directed to begin depositing the modeling material, and stop point **54** is a second location in the x-y plane at which extrusion head **20** is directed to stop depositing the modeling material. Accordingly, during the build operation, controller **30** directs extrusion head **20** to begin depositing the modeling material at start point **52**, and to move along contour tool path **40** in the direction of arrow **56** until reaching point **58**. Extrusion head **20** is then directed to follow the ring-geometry of contour tool path **40**, as illustrated by arrows **44**, until reaching point **60**. Extrusion head **20** is then directed to move along contour tool path **40** in the direction of arrow **62** until reaching stop point **54**, where extrusion head **20** stops depositing the modeling material.

This process provides a continuous road of the deposited modeling material at all locations around perimeter path **38** except at the intersection between points **58** and **60**, where the outgoing and incoming roads meet. This intersection forms a seam for layer **36** (referred to as seam **64**). As shown, start point **52** and stop point **54** are each located at an offset location from seam **64** within interior region **50**. This is in comparison to start and stop points generated under a conventional data generation technique, in which the start and stop points would typically be collinear with the outer ring of contour tool path **40** (i.e., at points **58** and **60**, respectively). Under the conventional technique, a contour tool path is typically generated to match the geometry of the exterior perimeter of a 3D model layer, with an offset that accounts for the road width (e.g., road width **42**). Thus, the start and stop points would necessarily be located at locations that are collinear with the contour tool path, and the stop point would end up being located next to the start point (e.g., at points **58** and **60**).

Due to variations in the extrusion process when starting and stopping the depositions, the modeling material deposited at a stop point corresponding to point **60** may bump into the modeling material previously deposited at a start point corresponding to point **58**. This bumping can form a significant bulge of the modeling materials at the seam, which can be visually observed with the naked eye, thereby detracting from the aesthetic qualities of the resulting 3D model. Alternatively, if not enough modeling material is deposited between points **58** and **60**, a gap may be formed at the seam, which can increase the porosity of the 3D model. The increased porosity can allow gases and fluids to pass into or through the 3D model, which may be undesirable for many functional purposes (e.g., for containing liquids). Accordingly, under the conventional data generation technique, proper seam sealing may be difficult to achieve, particularly due to the number of geometric complexities that may be required for a given 3D model.

Pursuant to the method of the present disclosure, however, seam **64** may be properly sealed by adjusting the location of the start point from point **58** to point **52**, and by adjusting the location of the stop point from point **60** to point **54**. This allows any variations in the extrusion process when starting and stopping the depositions to occur at a location that is within interior region **50** rather than adjacent to exterior surface **46**. Any variations (e.g., bulges) that occur within interior region **50** are masked by the successive layers of 3D model **26**, thereby concealing these effects within the filled body of 3D model **26** when completed. This allows the dimensions of perimeter path **38** at seam **64** to be truer to the dimensions of the digital representation of 3D model **26** and increases the consistency of the seams of successive layers of 3D model **26**.

While shown at particular x-y coordinates within interior region **50**, start point **52** and/or stop point **54** may alternatively be adjusted to a variety of different coordinate locations within interior region **50**. Additionally, the coordinate locations may vary depending on the dimensions of the particular layer of the 3D model being built. In the embodiment shown in FIG. **3**, start point **52** and stop point **54** are adjusted respectively from points **58** and **60** by vectors that are orthogonal to contour tool path **40** at perimeter path **38**, and which point toward interior region **50**. Examples of suitable distances for adjusting start point **52** from point **58** and/or for adjusting stop point **54** from point **60** (i.e., from a centerline of perimeter path **38**) includes distances that are greater than 50% of road width **42** (i.e., beyond interior surface **48**), with particularly suitable distances ranging from greater than about 50% of road width **42** to about 200% of road width **42**, and with even more particularly suitable distances ranging from about 75% of road width **42** to about 150% of road width **42**.

The locations of start point **52** and stop point **54** also allow the deposited modeling material to form a seal at seam **64** that extends inward within interior region **50**. This reduces the porosity of 3D model **26** at seam **64**, thereby reducing or eliminating the transmission of gases and/or liquids through seam **64**. As a result, in comparison to the conventional techniques, the process of adjusting the start and stop points to locations within interior region **50** effectively eliminates the formation of bulges of modeling material at seam **64**, while also reducing the porosity at seam **64**.

FIG. **4** is a flow diagram of method **66** for generating data and building a 3D model based on a digital representation of the 3D model, where the resulting 3D model includes concealed seams. The following discussion of method **66** is made with reference to 3D model **26** (shown in FIG. **1**) and layer **36** of 3D model **24** (shown in FIGS. **2** and **3**). However, method **66** is applicable for building 3D models and corresponding support structures having a variety of different geometries. As shown in FIG. **4**, method **66** includes steps **68-84**, and initially involves receiving a digital representation of 3D model **24** (step **68**), slicing the digital representation and into multiple layers (step **70**), and generating one or more pre-sliced support structures with computer **12** (step **72**). In an alternative embodiment, steps **70** and **72** may be reversed such that one or more support structures are generated and the digital representation and the generated support structure(s) are then sliced.

Computer **12** then selects a first layer of the sliced layers and generates one or more contour tool paths based on the perimeter of the layer (step **74**). For example, computer **12** may generate a contour tool path that defines the outer ring for perimeter path **38**. In alternative examples, a given layer may include multiple contour tool paths for building multiple and

separate parts and/or may include an exterior and an interior contour tool path for a single part (e.g., having a hollow interior cavity). At this point, the start and stop points for each generated contour tool path are collinear with the perimeter of the layer.

Computer **12** may then adjust the locations of the start point and/or the stop point to coordinate locations that are within the interior region for each generated contour tool path (step **76**). For example, computer **12** may adjust the start point from point **58** to point **52**, and may adjust the stop point from point **60** to point **54**. This places start point **52** and stop point **54** within interior region **50**. In an alternative embodiment, steps **74** and **76** of method **66** may be performed in a single step. In this embodiment, the adjustment locations of the start and stop points may be generated along with the generation of the contour tool path(s) (e.g., as predefined offset locations).

After the start and stop points are positioned in the interior region of the layer (e.g., within interior region **50** of layer **36**), computer **12** may then generate additional tool paths (e.g., raster paths) to bulk fill the interior region (step **78**). In this step, the generated additional tool paths desirably account for the locations of start point **52** and stop point **54**, and the segments of contour tool path **40** that extend into interior region **50**. When the layer is completed, computer **12** may then determine whether the current layer is the last of the sliced layers (step **80**). In the current example, layer **36** is not the last layer. As such, computer **12** may select the next layer (step **82**) and repeat steps **74-82** until the last layer is completed.

When the last layer is completed, computer **12** may transmit the resulting data to system **10** for building 3D model **26** and support structure **28** (step **84**). During the build operation, extrusion head **20** follows the patterns of the tool paths for each layer, including the contour tool paths with the adjusted start and stop points. As such, each layer of 3D model **26** and/or of support structure **28** may include a concealed seam having start and stop points located within the interior region of the given layer. Furthermore, the seams of adjacent layers may be offset from each other, thereby further obscuring the locations of the seams.

FIGS. **5-13** are alternative sectional views of section 3 shown in FIG. **2**, illustrating layers **136-936**, which are alternatives to layer **36** (shown in FIGS. **2** and **3**) having different start and stop points, and where the references labels are increased by 100-900, respectively. As shown in FIG. **5**, layer **136** includes contour tool path **140** having start point **152** and stop point **154** in a closed-square arrangement. In this embodiment, start point **152** is positioned at the same coordinate location within interior region **150** as start point **52** (shown in FIG. **3**). The location of stop point **154**, however, causes contour tool path **140** to turn at corner point **186**. As such, contour tool path **140** extends inward from point **160** in the direction of arrow **162**, and turns in the direction of arrow **188** at corner point **186** toward stop point **154**. This arrangement further reduces the porosity of layer **136** by creating a bend of the deposited roads of build material within interior region **150**.

As shown in FIG. **6**, layer **236** includes contour tool path **240** having start point **252** and stop point **254** in an overlapped closed-square arrangement. In this embodiment, start point **252** and stop point **254** are positioned at the same coordinate location within interior region **250** (i.e., stop point **254** overlaps start point **252**). This arrangement also includes corner point **286**, which bends contour tool path **240** in the same manner as discussed above for corner point **186** (shown in FIG. **5**), which is beneficial for reducing porosity while also concealing seam **264**.

The embodiment shown in FIG. **6** may be performed by gradually increasing the volumetric flow rate of the modeling material as extrusion head **20** travels between start point **252** and point **258**, and also by gradually reducing the reducing the volumetric flow rate of the modeling material as extrusion head **20** travels between point **260** and stop point **254**. For example, when extrusion head **20** travels along contour tool path **240** between start point **252** and point **258** in the direction of arrow **256**, controller **30** may direct extrusion head **20** to gradually increase the volumetric flow rate from zero up to 100% of the standard operational rate. Extrusion head **20** may then deposit the modeling material at 100% of the standard operational rate while forming perimeter path **238** along arrows **244**. Then, when extrusion head **20** travels along contour tool path **240** between point **260** and stop point **254** in the directions of arrows **262** and **288**, controller **30** may direct extrusion head **20** to gradually reduce the volumetric flow rate from 100% of the standard operational rate down to zero. This process reduces the amount of modeling material that is accumulated along the vertical z-axis at the intersection of start point **252** and stop point **254**.

As shown in FIG. **7**, layer **336** includes contour tool path **340** having start point **352** and stop point **354** in an open-triangle arrangement. In this embodiment, start point **352** and stop point **354** extend at angles relative to the orthogonal directions of start point **52** and stop point **54** (shown in FIG. **3**). In this embodiment, the corner points that direct contour tool path **340** into and out of interior region **350** (i.e., points **358** and **360**) are desirably offset from each other by a distance that is about 90% of road width **342** to about 100% of road width **342**. This allows seam **364** to be properly sealed at exterior surface **346** of perimeter path **338**.

As shown, start point **352** is positioned at a coordinate location within interior region **350** that is offset at angle α from the orthogonal axis to contour tool path **340** at perimeter path **338** (i.e., taken at point **358**). Similarly, stop point **354** is positioned at a coordinate location within interior region **350** that is offset at angle β from the orthogonal axis to contour tool path **340** at perimeter path **338** (i.e., taken at point **360**). Angles α and β may be the same values from their respective orthogonal axis, or may be different values, which may be affected by the geometry of layer **336**. Examples of suitable angles for each of angle α and angle β range from zero degrees (i.e., parallel to the orthogonal axis, as shown in FIG. **3**) to about 60 degrees, with particularly suitable angles ranging from about 30 degrees to about 45 degrees. The angled locations of start point **352** and stop point **354** reduce the extent that start point **352** and stop point **354** extend into interior region **350**. This is arrangement suitable for use with 3D models having thin-walled regions.

As shown in FIG. **8**, layer **436** includes contour tool path **440** having start point **452** and stop point **454** in a closed-triangle arrangement. In this embodiment, start point **452** extends at an angle relative to the orthogonal direction of start point **52** (shown in FIG. **3**) in a similar manner to that discussed above for start point **352** (shown in FIG. **7**). Furthermore, this arrangement includes corner point **486**, which bends contour tool path **440** in a similar manner to that discussed above for corner point **186** (shown in FIG. **5**). This combination further reduces porosity, and also further reduces the extent that start point **452** and stop point **454** extend into interior region **450**. As such, this embodiment is also suitable for use with 3D models having thin-walled regions.

As shown in FIG. **9**, layer **536** includes contour tool path **540** having start point **552** and stop point **554** in a converging-point arrangement. In this embodiment, start point **352** and stop point **354** are positioned closer to each other compared to points **558** and **560**. The corner points that direct contour tool path **540** into interior region **550** (i.e., points **558** and **560**) are also desirably offset from each other by a distance about equal to the road width of perimeter path **538**. As such, start point **552** and stop point **554** are offset from each other by a distance that is less than the road width.

This embodiment may be performed by gradually increasing the volumetric flow rate of the modeling material as extrusion head **20** travels along contour tool path **540** in the direction of arrow **556** between start point **552** and point **558**. Similarly, as extrusion head **20** travels along contour tool path **540** in the direction of arrow **562** between point **560** and stop point **554**, the volumetric flow rate may gradually decrease. This allows proper amounts of modeling material to be deposited at seam **564** and also reduces the amount of modeling material that is accumulated along the vertical z-axis at the intersection between start point **552** and stop point **554**.

As shown in FIG. **10**, layer **636** includes contour tool path **640** having start point **652** and stop point **654** in an overlapped-cross arrangement. In this embodiment, the relative locations of start point **652** and stop point **654** cause contour tool path **640** to overlap at seam **664**. This embodiment may also be performed by gradually adjusting the volumetric flow rate of the modeling material as extrusion head **20** travels along contour tool path **640**. For example, the volumetric flow rate may be decreased from 100% of the standard operational rate at point **660** down to zero at stop point **654**. However, in this embodiment, it is desirable for the volumetric flow rate of the modeling material to be substantially decreased at or shortly after point **660** to reduce the amount of modeling material that is accumulated along the vertical z-axis a seam **664**.

Accordingly, during a build operation, extrusion head **20** may initially follow contour tool path **640** from start point **652** to point **658** in the direction of arrow **656**. The volumetric flow rate of the modeling material may also be gradually increased at this stage. Extrusion head **20** may then deposit the modeling material at 100% of the standard operational rate while forming perimeter path **638** along arrows **644**. Then, extrusion head **20** travels along contour tool path **640** in the direction of arrow **662** between point **660** and stop point **654**, overlapping the previously deposited modeling material. As such, as extrusion head **20** travels in the direction of arrow **662**, the volumetric flow rate may be decreased to reduce the amount of modeling material that is accumulated along the vertical z-axis at seam **664**. The overlapping arrangement shown in FIG. **10** further reduces porosity by effective overlapping the intersection at seam **664**. In additional embodiments, contour tool path **640** may further bent within interior region **650** to position stop point **654** at or adjacent to start point **652**, as discussed above for the embodiments of layers **136** and **236** (shown in FIGS. **5** and **6**, respectively).

FIGS. **11** and **12** illustrate additional alternative embodiments in which the contour tool path also functions as an interior raster path to fill at least a portion of the interior region. As shown in FIG. **11**, layer **736** includes contour tool path **740** having start point **752** located adjacent to exterior surface **746**. As such, in this embodiment, start point **752** is not adjusted to a location within interior region **750**. However, the stop point of contour tool path **740** (not shown) is adjusted to a location within interior region **750** and contour tool path **740** is generated to at least partially fill interior region **750** with a raster pattern.

During a build operation, extrusion head **20** initially follows contour tool path **740** from start point **752** in the direction of arrow **744** to form perimeter path **738**. Upon reaching point **760**, extrusion head **20** then turns and follows contour tool path **740** in the direction of arrow **762** and continues to deposit the modeling material in a back-and-forth raster pattern within interior region **750**. This embodiment is beneficial for reducing the number of times that a tip of extrusion head **20** needs to be picked up and moved. Since this process can be performed with each layer of 3D model **26** and support structure **28**, this can provide substantial time savings when building 3D model **26** and support structure **28** in system **10**.

Additionally, start point **752** and the stop point for contour tool path **740** may also be positioned at locations in the x-y plane that will maximize the area of interior region **750** that is filled with the raster pattern of contour tool path **740**. For example, after generating contour tool path **740**, pursuant to step **74** of method **66** (shown in FIG. **4**), the start and stop points may be repositioned around the perimeter to a point that maximizes the raster pattern fill within interior region **750** before reaching the stop point. This further reduces the number of times that a tip of extrusion head **20** needs to be picked up and moved for building each layer. Furthermore, the generated raster pattern for contour tool path **740** may be offset by an angle between each successive layer (e.g., by 90 degrees). As a result, repositioning the start and stop points in this manner will cause the seams of each successive layer to be positioned at different locations in the x-y plane. This further conceals the seams of a 3D model (e.g., 3D model **26**) by staggering the locations of the seams between successive layers.

As shown in FIG. **12**, layer **836** includes contour tool path **840** having both start point **852** and the stop point (not shown) located within interior region **850**, where contour tool path is generated to at least partially fill interior region **850** with a raster pattern, as discussed above for layer **736** (shown in FIG. **11**). In the embodiment shown in FIG. **12**, however, start point **852** is also located within interior region **850**, desirably at an angle that substantially follows the raster pattern of contour tool path **840**. This combines the process time savings attainable with the integrated raster pattern along with the reduced porosity that is achieved by positioning start point **852** within interior region **850**. These benefits are in addition to the concealment of seam **864**, which allows the dimensions of perimeter path **838** at seam **864** to be truer to the dimensions of the digital representation of 3D model **26** and increases the consistency of the seams of successive layers of 3D model **26**.

As shown in FIG. **13**, layer **936** includes contour tool path **940** having start point **952** and stop point **94** in a crimped-square arrangement. In this embodiment, start point **952** is positioned within interior region **950** such that contour tool path **940** turns at corner points **986***a* and **986***b*. During a build operation, extrusion head **20** initially follows contour tool path **940** from start point **952** in the direction of arrows **956***a*, **956***b*, and **956***c*, until it reaches point **958**. Extrusion head **20** may form perimeter path **938** along arrows **944** until it reaches point **960**. Extrusion head **20** may then turn inward until it reaches stop point **954**. In an alternative embodiment, start point **952** and stop point **954** may be flipped such that the crimped square geometry is formed around start point **952**. The arrangement depicted in FIG. **13** positions start point **952** and stop point **954** within interior region **950**, while also further reducing the porosity of layer **936** by crimped square of the deposited roads of build material within interior region **950**.

FIGS. **14** and **15** illustrate layer **1036**, which is an additional alternative to layer **36** (shown in FIGS. **2** and **3**), where the reference labels are increased by 1000. As shown in FIG. **14**, layer **1036** includes perimeter paths **1038***a* and **1038***b*, which are a pair roads of a modeling material that is deposited

by extrusion head **20** along contour tool path **1040** in two passes, as represented by arrows **1044** (first pass to form perimeter path **1038***a*) and arrows **1090** (second pass to form perimeter path **1038***b*). As further shown, perimeter path **1038***a* includes exterior surface **1046** and perimeter path **1038***b* includes interior surface **1048**. Exterior surface **1046** is the outward-facing surface of perimeter path **1038***a*, which may be observable when 3D model **26** is completed. Interior surface **1048** is the inward-facing surface of perimeter path **1038***b*, which defines interior region **1050**. Interior region **1050** is the region of layer **1036** confined within perimeter paths **1038***a* and **1038***b*, and may be filled with additional modeling material deposited along additionally generated tool paths (e.g., raster paths, not shown).

As shown in FIG. **15**, contour tool path **1040** includes start point **1052** and stop point **1054**, where stop point **1054** is located within interior region **1050**. Accordingly, during the build operation, controller **30** directs extrusion head **20** to begin depositing the modeling material at start point **1052**, and to move along contour tool path **1040** in the direction of arrows **1044** until reaching point **1092**. This substantially forms perimeter path **1038***a*. At this point, while continuing to deposit the modeling material, extrusion head **20** steps over from perimeter path **1038***a* to begin forming perimeter path **1038***b* at point **1094**. Extrusion head **20** then continues to moves along contour tool path **1040** in the direction of arrows **1090** until reaching stop point **1054**. This forms perimeter path **1038***b*.

As shown, stop point **1054** is adjusted to a location within interior region **1050**. As such, seam **1064** also extends inward within interior region **1050**. This effectively eliminates the formation of bulges of modeling material at seam **1064**. Additionally, the step-over arrangement also reduces the porosity of 3D model **26** at seam **1064**, thereby reducing or eliminating the transmission of gases and/or liquids through seam **1064**.

In an alternative embodiment, start point **1052** and stop point **1054** may be flipped such that start point **1052** is located within interior region **1050**. In this embodiment, when extrusion head **20** reaches stop point **1054** (at the location of start point **1052** in FIG. **15**), extrusion head **20** may step back again toward the location of stop point **1054** in FIG. **15**, thereby creating an X-pattern at seam **1064**. The volumetric flow rate of the modeling material is desirably reduced when stepping back again to reduce the amount of the modeling material that is accumulated along the vertical z-axis at seam **1064**.

In additional alternative embodiments, the step-over arrangement may be continued to form additional perimeter paths **1038**, thereby increasing the overall thickness of the perimeter paths. These embodiments are beneficial for use with thin-walled regions where the formation of raster patterns may be more time consuming. Furthermore, the embodiments discussed in FIGS. **14** and **15** may be combined with the raster pattern embodiments shown in FIGS. **11** and **12**. In these embodiments, contour tool path **1040** may step over into the raster pattern to fill at least a portion of interior region **1050**.

FIG. **16** is an alternative sectional view of section 15 shown in FIG. **14**, illustrating layer **1136**, which is an alternative to layer **1036** (shown in FIGS. **14** and **15**) having a different stop point, and where the references labels are increased by 100. As shown in FIG. **16**, contour tool path **1140** of layer **1136** includes start point **1152** and stop point **1154**, where start point **1152** is located at the same position as start point **1052** (shown in FIG. **15**). Stop point **1154**, however, stops the deposition of the modeling material prior to forming a complete ring for perimeter path **1138***b*. While shown at the particular location in FIG. **16**, stop point **1054** may be located at any distance from point **1194**. This embodiment is also suitable for extending seam **1164** inward within interior region **1150**, thereby effectively eliminating the formation of bulges of modeling material at seam **1164**. Additionally, the step-over arrangement also reduces the porosity of 3D model **26** at seam **1164** and the shortened length of perimeter path **1138***b* is beneficial for use in thin-wall regions.

EXAMPLES

The present disclosure is more particularly described in the following examples that are intended as illustrations only, since numerous modifications and variations within the scope of the present disclosure will be apparent to those skilled in the art. Build operations were preformed with the method of the present disclosure to fabricate 3D models of Examples 1-4, each having concealed seams. Each 3D model of Examples 1-4 were built from the same digital representation having a filled cylindrical geometry.

For each 3D model of Examples 1-4, the digital representation was provided to a computer capable of communicating with an extrusion-based digital manufacturing system. The computer then sliced the digital representation into multiple layers with a software program commercially available under the trade designation "INSIGHT" from Stratasys, Inc., Eden Prairie, Minn. The software program also generated contour tool paths for each sliced layer. In addition, the start and stop points of each contour tool path were adjusted to predefined locations within the interior regions defined by the respective contour tool paths.

The start and stop points for Example 1 were adjusted to an open-square arrangement as depicted in layer **36** (shown in FIG. **3**). The start and stop points for Example 2 were adjusted to an overlapped closed-square arrangement as depicted in layer **236** (shown in FIG. **6**). The start and stop points for Example 3 were adjusted to an converging-point arrangement as depicted in layer **536** (shown in FIG. **9**). The start and stop points for Example 4 were adjusted to an overlapped-cross arrangement as depicted in layer **536** (shown in FIG. **10**). For each modified contour tool path, raster tool paths were then generated within the interior regions, where the raster tool paths accommodated the adjustments to the start and stop locations of the contour tool paths.

In addition to the 3D models of Examples 1-4, a 3D model of Comparative Example A was prepare from the same digital representation and using the same above-discussed steps. However, for Comparative Example A, the start and stop locations of the contour tool paths were not adjusted. As such, the start and stop locations remained collinear with the outer rings of the contour tool paths.

For each 3D model of Examples 1-4 and Comparative Example A, the resulting data was then transmitted to the extrusion-based digital manufacturing system, which was a fused deposition modeling system commercially available under the trade designation "FORTUS 400mc" from Stratasys, Inc., Eden Prairie, Minn. Based on the received data, the system then built each 3D model from an acrylonitrile-butadiene-styrene (ABS) copolymer modeling material.

After the build operations were completed, the perimeter path seams of each 3D model was visually inspected. For the 3D model of Comparative Example A, the perimeter path seams exhibited surface bulges of modeling material that were readily identifiable by the naked eye. In comparison, however, the perimeter path seams of the 3D models of each of Examples 1-4 did not exhibit any surface bulging and were consistent between the successive layers. As such, the method of the present disclosure is suitable for effectively concealing the seams of the perimeter paths (created by the contour tool paths). As discussed above, this may increase the aesthetic and functional qualities of the resulting 3D models.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

The invention claimed is:

1. A method for building a three-dimensional model with an extrusion-based digital manufacturing system, the method comprising generating a contour tool path that defines an interior region of a layer of the three-dimensional model, wherein the contour tool path comprises a start point, a stop point, and a step-over arrangement between the start point and the stop point, wherein the step-over arrangement is oriented at a non-right angle, wherein at least one of the start point and the stop point is located within the interior region of the layer, and wherein the step-over arrangement reduces surface porosity for the three-dimensional model.

2. The method of claim **1**, and further comprising adjusting the at least one of the start point and the stop point from a first coordinate location to the location within the interior region of the layer.

3. The method of claim **1**, wherein the location of the at least one of the start point and the stop point is substantially orthogonal to a direction of the contour tool path at a perimeter of the layer.

4. The method of claim **1**, wherein the location of the at least one of the start point and the stop point is offset from a centerline of a layer perimeter by a distance ranging from greater than about 50% of a road width used to generate the contour tool path to about 200% of the road width.

5. The method of claim **1**, wherein the start point and the stop point are each located within the interior region of the layer.

6. The method of claim **1**, wherein the locations of the start point and the stop point define an arrangement selected from the group consisting of an open-square arrangement, a closed-square arrangement, an overlapped closed-square arrangement, an open-triangle arrangement, a closed-triangle arrangement, a converging-point arrangement, an overlapped-cross arrangement, a crimped-square arrangement, and combinations thereof.

7. The method of claim **1**, wherein the contour tool path between the start point and the stop point further defines a raster path that at least partially fills the interior region.

8. The method of claim **7**, and further comprising positioning the start point and stop point to substantially maximize the amount of the interior region that is filled with the raster path.

9. The method of claim **1**, and further comprising extruding a material in a pattern based on the generated contour tool path to form a perimeter of the extruded material for one of the layers of the three-dimensional model, the perimeter of the extruded material comprising a start point, a stop point, and a non-right angle step-over arrangement between the start point and the stop point, wherein the perimeter defines an interior region of the layer of the three-dimensional model, and wherein at least one of the start point and the stop point is located within the interior region of the layer of the three-dimensional model.

10. A method for building a three-dimensional model with an extrusion-based digital manufacturing system, the method comprising:

receiving a digital representation of the three-dimensional model;

slicing the received digital representation into a plurality of layers;

generating a contour tool path based on a perimeter of a first layer of the plurality of layers, wherein the generated contour tool path defines an interior region of the first layer;

adjusting a start point of the contour tool path and a stop point of the contour tool path to locations within the interior region to provide a modified contour tool path; and

extruding a material in a pattern based on the modified contour tool path to form a perimeter of the extruded material for one of the layers of the three-dimensional model, the perimeter of the extruded material comprising a start point and a stop point, and defining an interior region of the layer of the three-dimensional model, wherein the start point and the stop point of the perimeter of the extruded material are each located within the interior region of the layer of the three-dimensional model.

11. The method of claim **10**, and further comprising:

repeating the generating and adjusting steps for each remaining layer of the plurality of layers of the digital representation to provide modified contour tool paths for each of the remaining layers; and

extruding the material in patterns based on the modified contour tool paths for each of the remaining layers to form perimeters of the extruded material for remaining layers of the three-dimensional model.

12. The method of claim **10**, wherein the location of the at least one of the start point and the stop point of the perimeter of the extruded material is offset from the formed perimeter of the extruded material by a distance greater than about 50% of a road width of the extruded material.

13. The method of claim **10**, wherein the modified contour path comprises at least one step-over arrangement oriented at a non-right angle between the start point and the stop point.

14. The method of claim **10**, wherein the locations of the start point and the stop point of the perimeter of the extruded material define an arrangement selected from the group consisting of an open-square arrangement, a closed-square arrangement, an overlapped closed-square arrangement, an open-triangle arrangement, a closed-triangle arrangement, a converging-point arrangement, an overlapped-cross arrangement, and combinations thereof.

15. A method for building a three-dimensional model with an extrusion-based digital manufacturing system, the method comprising:

generating a tool path that comprises:

a start point for the tool path;

a stop point for the tool path;

a contour tool path extending from the start point and based on a perimeter of a layer of the three-dimensional model, wherein the generated contour tool path defines an interior region of the layer; and

an interior raster path extending from the contour tool path within the interior region of the layer, wherein the interior raster path ends at the stop point; and

extruding a material in a pattern based on the generated tool path to form the perimeter and at least a portion of the interior of the layer of the three-dimensional model.

16. The method of claim **15**, and further comprising positioning the start point and stop point to substantially maximize the amount of the interior region that is filled with the interior raster path.

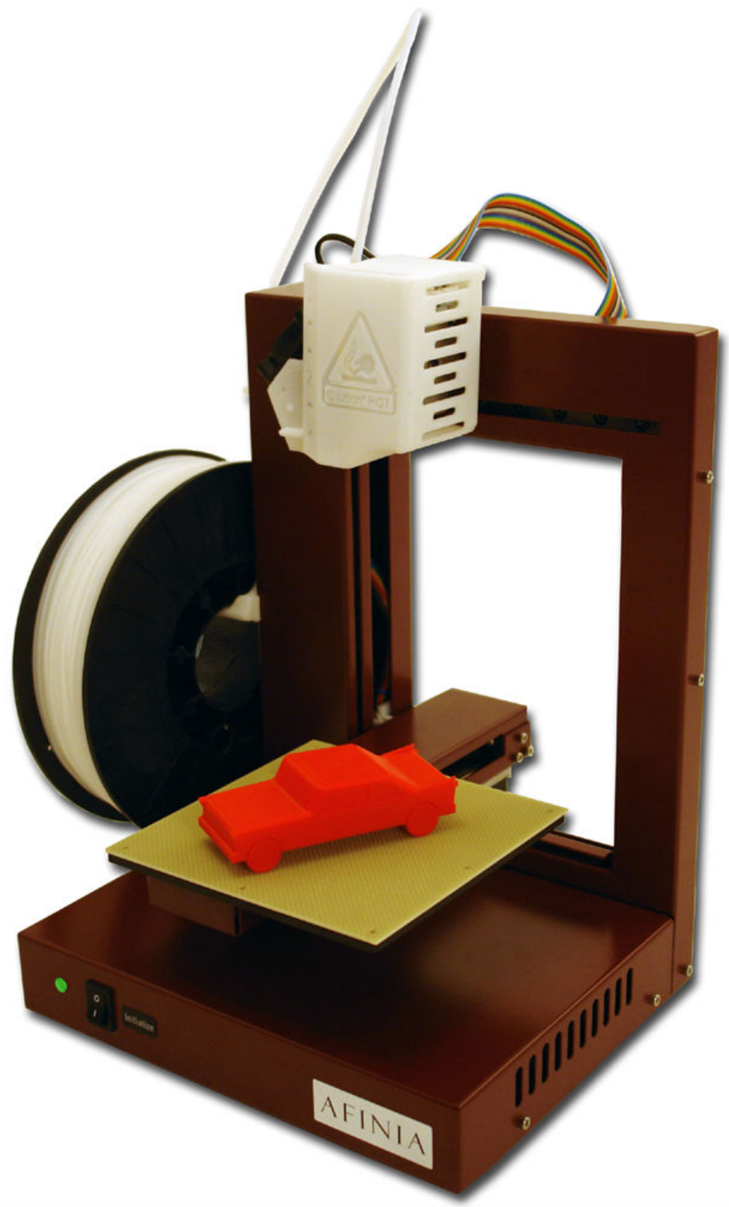
17. The method of claim **15**, wherein the contour path comprises at least one step-over arrangement oriented at a non-right angle.

18. The method of claim **15**, wherein the extruded material consists essentially of at least one thermoplastic material.

* * * * *

EXHIBIT E

AFINIA



H-Series 3D Printer

Version 2.0

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MB081

Afinia 1-Year Limited Warranty

Below is the one-year limited warranty included with this Afinia product. Afinia prides itself on its outstanding product line and its technical support. If for some reason, your product fails, Afinia, a division of Microboards Technology, LLC, stands behind its warranties and assures you the best service possible in a quick and timely manner.

Afinia warrants to the original purchaser that this product is free from defects in material and workmanship. Afinia will for one year, at its option, repair or replace at no charge for parts and labor from the date you purchased the product from an authorized Afinia reseller. Nozzles and Cell/Perf Boards are warranted for ninety (90) days.

• Warranty registration must be completed within 30 days of receipt of the product in order to validate the warranty.
• Afinia, a division of Microboards Technology, LLC, reserves the right to determine the validity of all warranty claims.
• Warranty is void if the product serial number has been altered or removed.
• Warranty is void if the product has been misused or damaged or if evidence is present that the product was altered, modified, or serviced by unauthorized service people.

The above stated warranty is exclusive and replaces all other warranties, express of implied, including those of merchantability and fitness for a particular purpose. Afinia, a division of Microboards Technology, LLC, will not be liable for any other damages or loss, including incidental or consequential damages and loss of profits or revenues from whatever cause, including breach of warranty or negligence.

This product has been thoroughly tested and inspected at the factory prior to shipment. Nevertheless, inspect your product completely for any damage or loss of parts that may have occurred during shipment. Notify the delivering carrier promptly if damage claims are to be filed.

Afinia reserves the right to modify or update its product without obligation to replace any equipment delivered prior to any such change.

To register your warranty, please visit www.afinia.com/register

FCC ID: 026-H479

This device complies with Part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) this device may not cause harmful interference, and (2) this device must accept any interference received, including interference that may cause undesired operation.

Changes or modifications not expressly approved by the party responsible for compliance could void the user's authority to operate the equipment.

NOTE: This equipment has been tested and found to comply with the limits for a Class B digital device, pursuant to Part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instructions, may cause harmful interference to radio communications. However, there is no guarantee that interference will not occur in a particular installation. If this equipment does cause harmful interference to radio or television reception, which can be determined by turning the equipment off and on, the user is encouraged to try to correct the interference by one or more of the following measures:

- Reorient or relocate the receiving antenna.
- Increase the separation between the equipment and receiver.
- Connect the equipment into an outlet on a circuit different from that to which the receiver is connected.
- Consult the dealer or an experienced radio/TV technician for help.

Introduction

Congratulations on purchasing an Afinia H-Series 3D Printer. The Afinia H-Series 3D Printer is designed with ultimate portability and simplicity in mind. The system and software allow you to print great models in a few easy steps, even if you have never used a 3D printer before. The Afinia H-Series 3D printer combines years of experience and innovation to make printing 3D models easy through its reliably simple hardware and software design.

Safety Precautions

Please read this section carefully before using the printer.

- The printer can only be used with the power adapters supplied by this company, or the product may be damaged, with a risk of fire.
- To avoid burning or model deformation, do not touch the model, nozzle, or the platform by hand or any other part of the body while the printer is working or immediately after it has finished printing.
- Protective glasses should always be worn when removing support material, especially PLA.
- The brown sections of the currently supplied gloves melt at around 200º C; please do not hold the extruder block with the gloves.
- There is a slight smell from ABS when it is being extruded. A well-ventilated room is recommended; however when printing, keep the printer away from any drafts as this can affect the warping of ABS prints.
- When ABS is burnt it releases toxic fumes. Never set the nozzle temperature high enough to burn the material.

The following classifications are used in this manual:

	CAUTION: Indicates a potentially hazardous situation which, if not avoided, may result in minor or moderate injury.
	WARNING: Indicates a potentially hazardous situation which, if not avoided, may result in serious injury.
	GLOVES: When performing certain maintenance procedures, the machine may be hot and gloves are required to avoid burns.
	SAFETY GLASSES: Wear safety glasses to avoid injury to your eyes.

Protection

- The printer must not be exposed to water or rain, or damage may occur.
- Do not shut down the Afinia H-Series 3D System or pull out the USB cable when loading a digital model or the model data may be lost.
- When using the "Extrude" function, keep at least 50mm between the nozzle and the platform. If too close, the nozzle may get blocked.
- The printer is designed to work properly at an ambient temperature of between 60°F and 85°F and humidity of between 20% and 50%. Operating outside these limits may result in low quality models.

Overview

The Afinia H-Series 3D Printer primarily consists of the Extruder, Print Platform, Material Spool, and Filament, all supported by the Pedestal. The Printer is initialized with a single switch, and calibrating the position of the print platform is done using the included Afinia software.

The Afinia 3D software sends the print data from a Mac or PC to the Printer over a single USB cable. The Print Platform moves both vertically and front-to-back while the Extruder moves left-to-right, providing the necessary 3 axes of operation (see Figure 2). The Extruder delivers the Filament from the Material Spool into the Nozzle, which heats the filament to printing temperature and deposits it on the Platform.

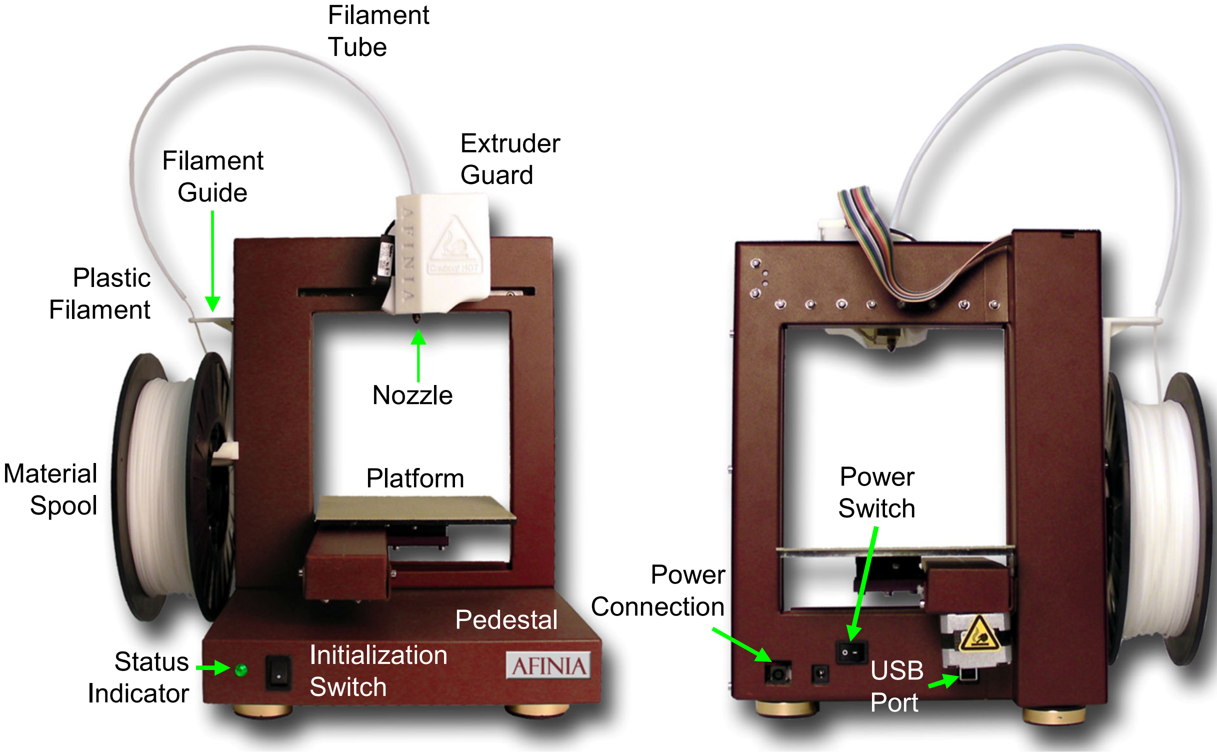
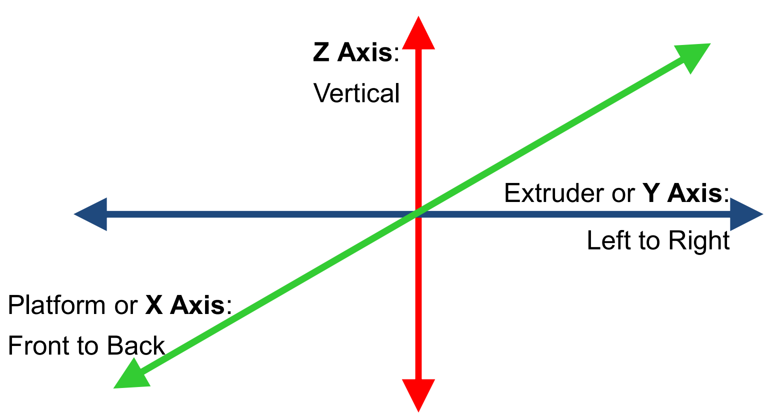


Figure 1: Front and Back views of the Afinia H-Series 3D Printer

Figure 2: Axes of Operation



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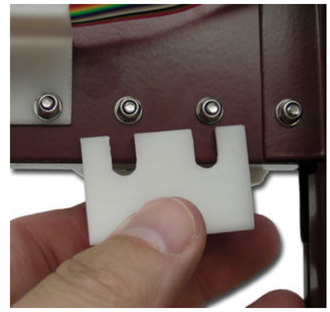
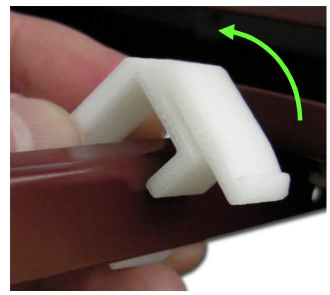
Unpacking the Afinia H-Series 3D Printer

Remove the Installation Disc, Manual, Quick Start Guide, and Accessories Pack from the box. Next, lift the Afinia H-Series 3D printer from the box. Remove the foam from both sides of the Printer and set the Printer on its base with the back of the Printer facing you.



There are 2 packaging clips that protect the Printer during shipping that need to be removed. ***Both clips should be saved in the event that you need to ship the Printer in the future!***

The first clip to be removed is used to hold the Extruder assembly in place during shipping. Carefully peel the strapping tape down, and then slide the clip down and off the Printer.



The second clip is used to help keep the Platform Arm secure during shipping. To remove the clip, place your hand under the platform X-axis arm and gently lift. Do not lift the arm by holding onto the platform!

Once the platform arm has been lifted a few inches, rotate the top of the clip towards the front of the printer. Once in the correct position, the clip will slip over the Z-axis arm.

Next, open and check the contents of the Accessory Pack:

- Reel of Filament (1, Natural/White)
- Power Supply
- Power Cable
- USB Cable
- FR-4 (Perf) Board
- FR-4 Board Clips (6)
- Filament Guide Tube
- Filament Hanger
- Nozzle Wrench
- Hex Wrenches
- Spare screws & washers
- Gloves (1 pair)
- Putty Knife
- Exacto Knife and blades
- Snipping Pliers
- Tweezers

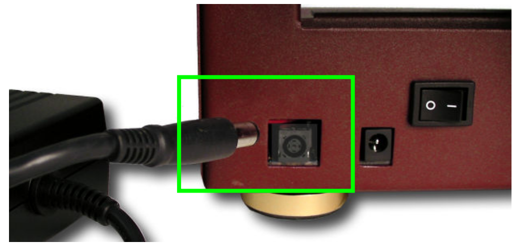
You will need the Power Supply and Cable, Hex Wrenches, Filament Spool, Filament Hanger, Filament Tube, and USB Cable to complete the Afinia H-Series 3D Printer installation.

Installing the Afinia H-Series 3D Printer

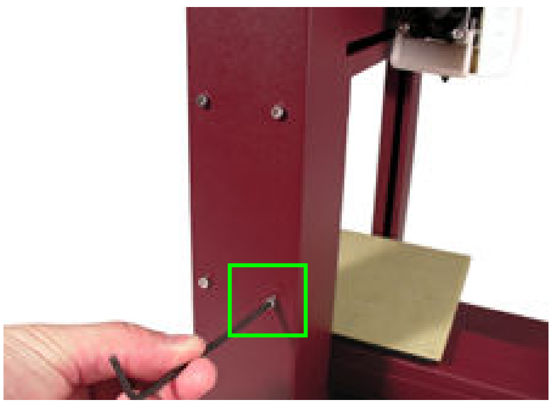
Attaching the Material Spool

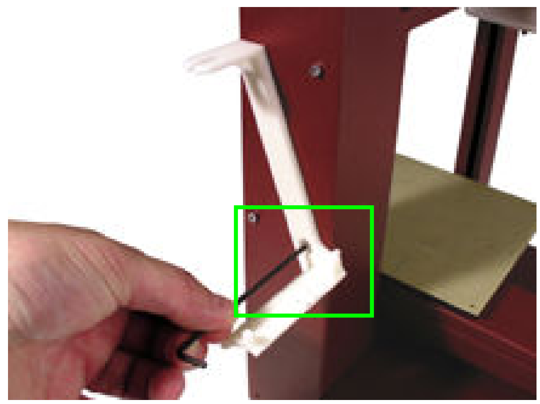
Attach the Material Spool with these steps:

A. Connect the power adapter to the power interface and turn on the power switch.

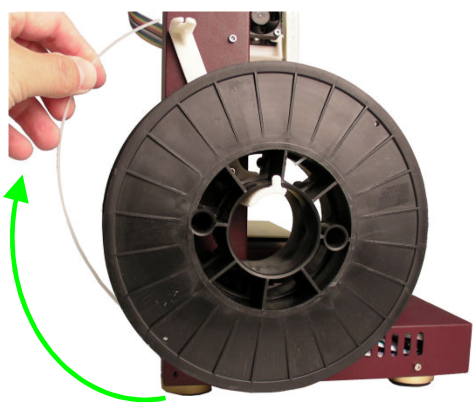


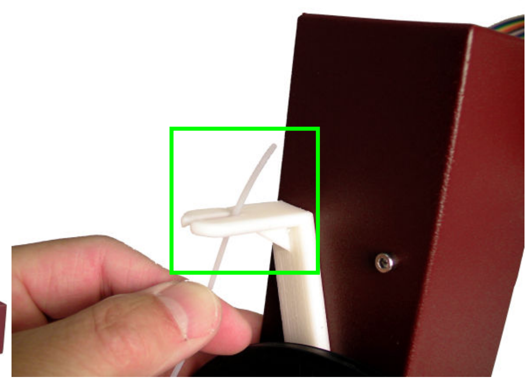
B. Install the ABS plastic spool holder and filament guide. Unscrew the lower right screw from the left side of the Printer. Use this same screw to attach the spool holder with the bottom right lip of the spool holder locked onto the printer's corner and the top of the holder mounted over the upper left screw.



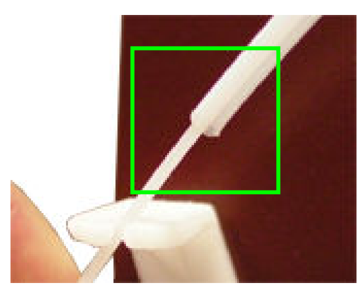


C. Put the ABS Material Spool onto the holder with the end of the filament pointing up from the back. Thread the filament through the Filament Guide at the top of the spool holder.





D. Insert the end of filament into one end of the Filament tube. Feed the filament through the tube until about 4 inches of filament protrudes from the tube.



Driver and Software Installation

Mac

Insert the Installation Disc into your Mac. Open the disc, go into the ***Mac*** folder, and double-click the **Afinia Mac Setup.pkg** icon. Follow the prompts through the installation. The drivers will be added and the Afinia software will be installed to the ***Applications*** folder.

Windows

Insert the Installation Disc into your PC. If the installer does not launch automatically, start the Afinia H-Series 3D Printer ***setup.exe*** file in the **PC** directory on the installation disc and install to the specified directory (default is ***Program files\Afinia\Afinia 3D Printer***).

Note: This installs the Afinia H-Series 3D Printer software, the Afinia H-Series 3D Printer drivers, and the Afinia H-Series 3D Printer sample files into your ***Program files\Afinia\Afinia 3D Printer*** folder.

Follow the instructions in the Installer to be sure the drivers and software are all in place before attempting to use the Printer. The instructions below will follow the same order as those in the Installer.

Installing the Printer

USB Connection

Mac

Simply connect the Printer to your Mac using the USB connection on the back of the Printer.

Windows Vista, and Windows 7

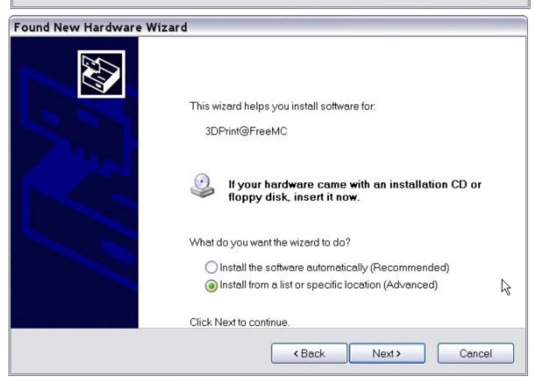
As part of the installation, the 3D Printer drivers are pre-installed and you will be prompted to connect the Printer to your PC. The Printer will be recognized and automatically installed when it is connected to your PC.

Windows XP

Since XP does not have the driver pre-installation ability, the drivers must be manually installed when the Printer is connected to the PC. Follow these steps:

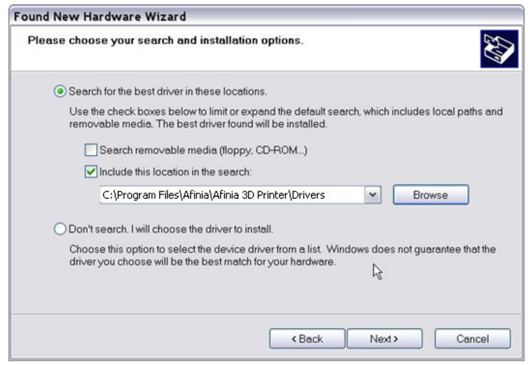
A. Connect the printer to a computer with the USB cable. If the computer displays the "Found New Hardware Wizard" window, choose **No, not this time**, and click the **Next** button.

B. Choose **Install from a list or specific location (Advanced)** and click **Next**.



C. Select the option to **Search removable media**; the drivers are located on the installation disc.

If you are installing from a download, click **Browse**, then navigate to ***C:\Program files\Afinia\Afinia 3D Printer\Driver***, then **Next**.

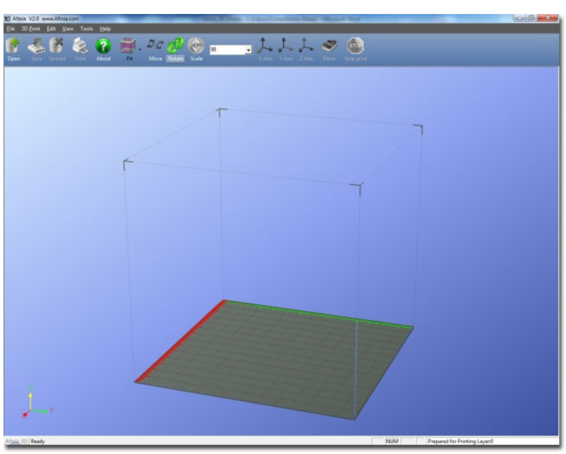


D. If the following dialog box appears, click **Continue Anyway**, and the drivers will install automatically.

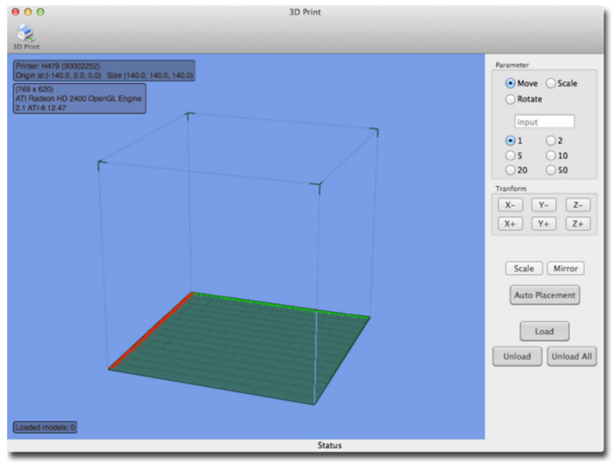
Getting Ready to Print

Starting the Afinia 3D Program

If the application is not already open, click the Afinia 3D icon on the desktop (Windows) or in the Applications folder (Mac). The program should open and appear as shown below:



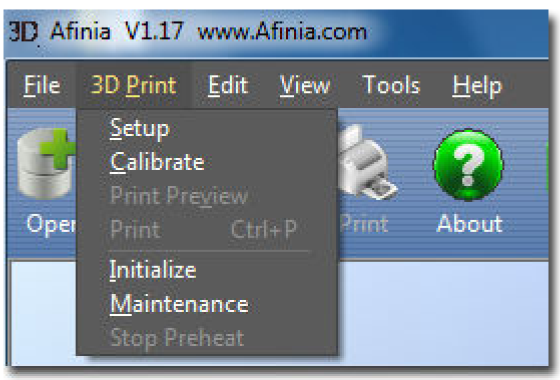
Windows version



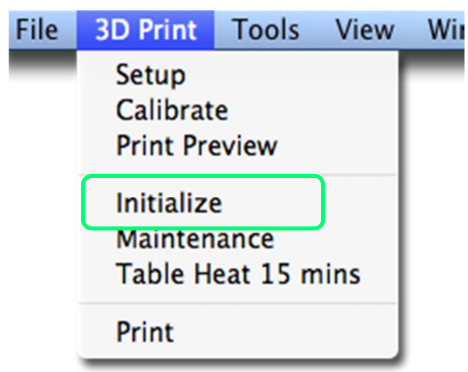
Mac version

Initializing the Printer

Before anything can be printed, the printer must be initialized. Click the **Initialize** option from the **3D Print** menu. The printer will beep and the initialization procedure will begin. The printer will return the platform and print head to the printer's origin and beep again when it is ready.



Windows version



Mac version

The front Initialization Switch can also be used for initialization. Hold down the Initialization Switch for one second to trigger the initialization procedure.

TIP: If your printer is not responding properly, the first thing to try is to re-initialize the printer by clicking the **Initialize** option from the **3D Print** menu.

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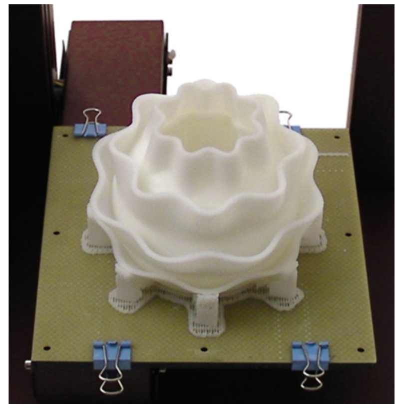
Preparing the Platform

Before you start printing, the platform must be prepared so that the model adheres to the platform enough to be printed without the model moving. At the same time, you will want the model to be easy to remove from the platform after printing. There are several options for preparing the platform:

FR-4 Board (Glass-reinforced Epoxy Laminate)

Many users have reported excellent results by using a piece of FR-4 Board to cover the build platform. FR-4 Board is a perforated, glass-reinforced epoxy laminate sheet.



When using FR-4 Board, the first layer of the raft pushes plastic into all the perforations, and this provides a strong mechanical bond with the surface that prevents it from later lifting. The FR-4 Board can be either taped down (with masking tape or double-sided tape), or clipped to the platform as shown in the picture to the right. Make sure the clips are on the front and back of the platform only to avoid interfering with the platform movement!

It can be easier to remove the model from the FR-4 Board after the model has cooled down. As the plastic cools, it shrinks away from the perforations, which make it easier to pull out.

Some FR-4 Boards may work better than others. For consistent printing, it is recommended that you use the FR-4 Board included with the Printer.

Borofloat Glass

Many users have reported success using Borofloat glass as the print surface. In this method, an ABS and acetone slurry is made in advance, which is lightly brushed onto the glass and allowed to dry into a thin film of ABS.

The ABS film will hold the model to the heated glass, and will release from the glass as the glass cools. If the model does not easily release, spray a small amount of an ammonia-based glass cleaner around the model.

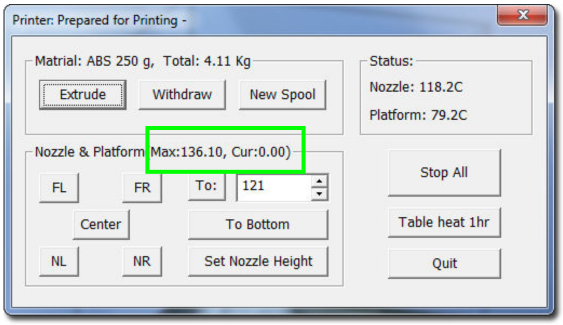
The same glass cleaner can be used to easily clean the film from the glass.

You will need to clean and recoat the print surface after each print if you will be printing the next model in the same location. Allow the slurry to dry fully before placing the glass on the print platform!

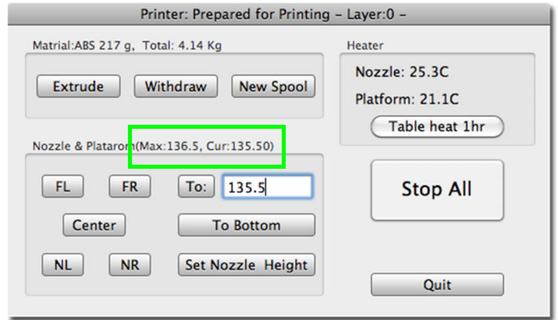
Whichever platform preparation method you use, the two factors that most reduce the risk of warping on large prints are ensuring that the platform is well leveled and well pre-heated.

Leveling the Print Platform

Before calibrating the nozzle height, always check the vertical nozzle distance from each corner and center of the print platform. Open the **Maintenance** dialog box from the **3D Print** menu and click the **Center** button to begin the leveling process.



Windows version

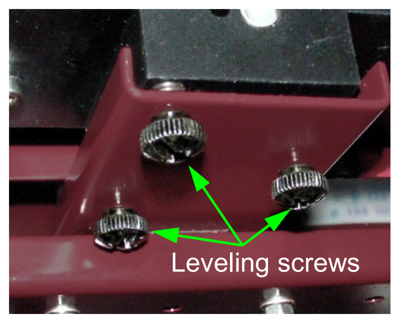


Mac version

If you already know the nozzle height, enter that height minus 2mm in the **To:** box, then click the **To:** button. If your nozzle height is 135.3, for example, enter **133.3**.

If you do not yet know the nozzle height, Click the **To:** button to bring the platform to the displayed height, then slowly increment the height until the platform is about 2 mm from the nozzle, clicking **To:** after each increase.

Use the five position buttons to check that the platform at all four corners and the center are the same distance from the nozzle.



If the platform is not the same distance from the nozzle at all five points, you will need to adjust the platform until it is level. There are 3 thumbscrews under the platform that are used to level the platform.

Loosening a thumbscrew will raise the related corner of the platform, while tightening the thumbscrew will lower the same part of the platform. Adjust the thumbscrews as needed until all four corners and center of platform are the same vertical distance from the nozzle.

Always recalibrate the nozzle height after leveling the platform.

Calibrating the Nozzle Height

This section is probably the most important of the entire manual. Please read it carefully to ensure that you understand the nozzle height setup procedure, as it is vital to successful 3D printing.

To print successfully, the platform should be set to start at a distance of 0.2mm from the nozzle. As each printer is slightly different, this distance needs to be calibrated before starting to print.

To determine the correct nozzle distance, please follow these steps:

1. Open the **Maintenance** dialog box from the **3D Print** menu and click the **Center** button. The current nozzle height is indicated as shown in the **Maintenance** dialog images above. In the Windows example, the platform is currently at the bottom of the printer; the Mac example has the platform 135.5mm from the bottom.
2. Enter the height to which you want the platform to move to into the textbox and click the **To** button. In the above Windows example, the platform will move to **121** mm above the platform's origin. In the Mac example, the platform is already at the height selected.

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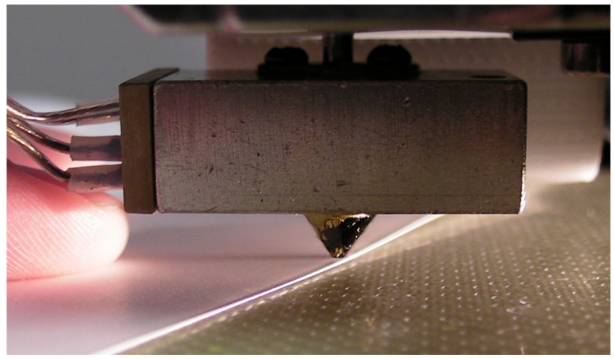
3. Check the distance between the nozzle and the platform. If the platform is currently at 121mm and appears to be about 12mm away from the nozzle, change the number in the text box to by 9mm to **130** and click the **To** button. Use small increments from there when calibrating the nozzle to avoid striking the platform into the nozzle.
4. Once you are about 1mm away from the nozzle, increase the number in the text box by 0.1mm increments and click the **To** button. Repeat until you get 0.2mm from the nozzle.

   TIP: An easy way to check the distance between the nozzle and platform is to fold a piece of paper in two, which will be about 0.2mm thick. Use this as a spacer to gauge the distance between the nozzle and platform.



5. Once you have the platform within 0.2mm of the nozzle, click the **Set Nozzle Height** button to save the current nozzle height.
6. Check the nozzle height at all four corners of the platform. Repeat the Platform Leveling and Nozzle Height Calibration processes if needed.

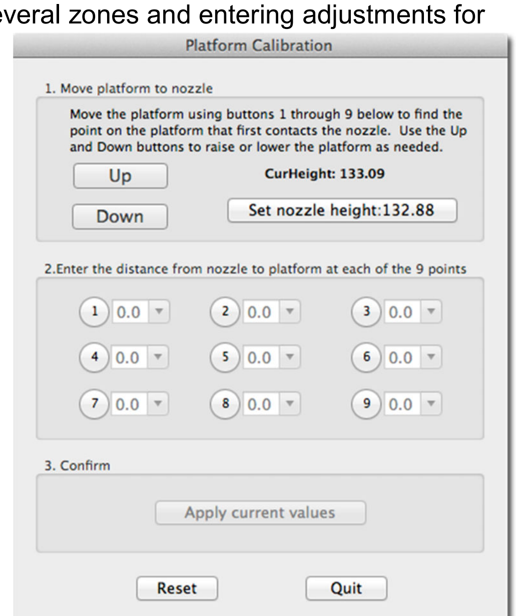
You may need to recalibrate the nozzle height after moving the printer or changing the printing platform if the models are not adhering to the platform properly or are warping.

TIP: If the platform contacts the nozzle while making height adjustments, it is good practice to re-initialize the printer and before undertaking any other operations.

Platform Level Calibration

This process is not intended to replace manually leveling the platform. It should only be used if your print surface itself cannot be leveled due to warping or an inconsistent thickness.

If the platform surface cannot be leveled after performing the leveling and nozzle height calibration, there is a utility in the Afinia software that allows you to adjust the printing of the raft to level the model printing layers by dividing the print platform into several zones and entering adjustments for each.



Note that this will only affect printing when using a raft; if you are printing raftless, this utility will not affect print leveling.

Select **Platform Calibrate** from the **3D Print** menu to open the utility.

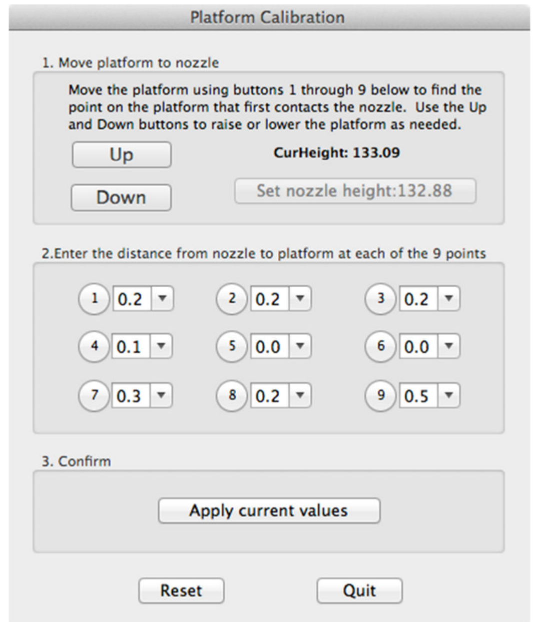
First, find the highest of the 9 points on the platform. Click the button labeled **5** to move the nozzle to the center of the platform. Use the **Up** button to raise the platform; holding the button down will move the platform steadily, while single clicks can be used to fine-tune the platform height.

Raise the platform until the platform is just touching the nozzle and note the current height.

Next, click the **Down** button a few times to lower the platform then click the **1** button to check the platform at the back left corner.

Raise the platform again until the platform is just touching the nozzle. If the current height is lower than the previous point when the platform and nozzle first contact each other, use this point as the reference.

Repeat these steps for each of the 9 points on the platform. Once you have determined the highest point on the platform, move back to that point and adjust the platform position so the nozzle is again just touching the platform. Click the **Set nozzle height** button to change the nozzle height setting to that shown.



Once the nozzle height is set, use the 9 buttons to move to each position. Select the distance from the drop-down to the right of the selected position, choosing the value that will bring the platform into contact with the nozzle.

Perform this step with each of the nine positions. If you are using clips to secure the print surface to the platform, be careful to position the clips so they do not interfere with the nozzle or wind barrier.

Once all 9 values have been entered, click the **Apply current values** button.

If you need to perform this function again, click the **Reset** button to clear all values.

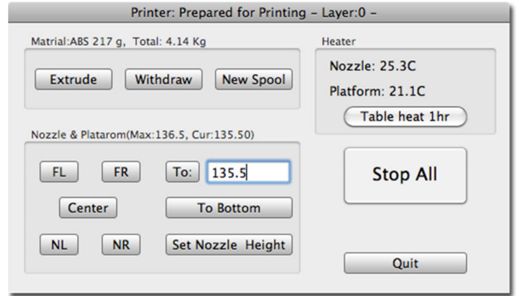
Click the **Quit** button when you are finished.

The adjustments in the example above, for instance, indicate that the print surface is warped, with the center higher than both the front and back edges. Using the Platform Level Calibration utility, you can correct for this warping.

This process is not intended to replace manually leveling the platform. It should only be used if your print surface itself cannot be leveled due to warping or an inconsistent thickness.

Loading the Print Material Filament

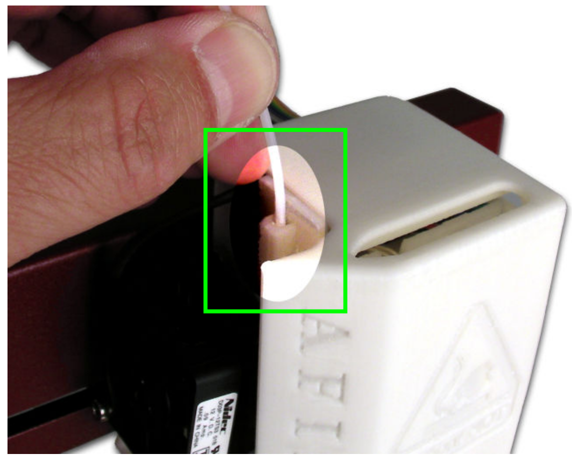
This process will be the same on both Mac and Windows.



A. Launch the Afinia H-Series 3D Software (refer to the software install procedure if you have not already installed it), and select **Maintenance** from the **3D Print** menu. Click the **Extrude** button. After the printer nozzle has warmed up to 260° C, the printer will beep; you can also monitor the nozzle temperature in the **Maintenance** window under the **3D Print** menu.

B. ***Be sure the filament is running through the filament tube between the spool holder and extruder!***

C. Once the nozzle is heated, push the end of the filament into the hole at the top of the extruder head and hold it there with gentle pressure until the extruder motor starts pulling it through the extrusion head. The extruder will extrude a thin filament of material for a short period of time.



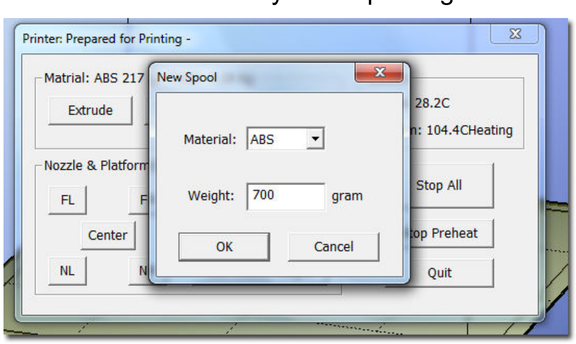
Other Maintenance Options

The **Extrude** button is used to load material into the nozzle. Click this button, and the nozzle will begin to heat. When the temperature is high enough (260° C), the material is squeezed out of the nozzle. The system beeps before material starts extruding, and it beeps again when finished. When changing the material (see page 29), use this function to load the new material to the nozzle. It can also be used to test whether the nozzle is working correctly.

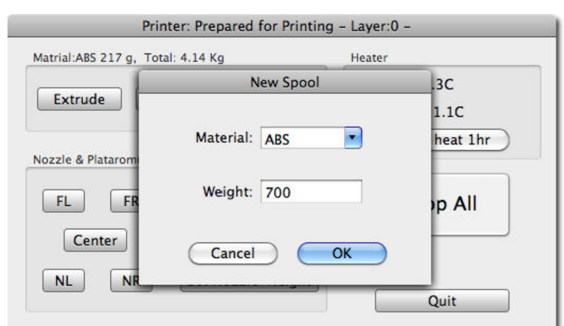
Use the **Withdraw** button to clear the filament from the nozzle when you change the filament or if the nozzle needs to be cleaned. Once the nozzle is up to temperature (260°C) and the printer beeps, gently pull out the material.

The **New Spool** button is used by the software to keep track of how much material has been used, and warn you if you don't have enough material left to print your model.

Click the button and enter the grams of material you have on the current spool. If it is a new spool, the weight should be set to the filament weight of the spool in grams. You can also specify whether the material you are printing with is ABS or PLA.



Windows version



Mac version

TIP: An empty Afinia Premium spool weighs about 280 grams. If you are installing a partially used Afinia Premium filament spool, weigh it, and subtract 280 grams from the weight. Enter that value into the material Weight text box.

Status
This area displays the current temperature of the nozzle and platform and if either element is currently being heated.

Nozzle & Platform Position Controls
The five buttons (**FL**, **FR**, **Center**, **NL**, **NR**) control the position of the nozzle and the platform. The nozzle moves to the left and right; the platform moves forward and backward.

The **To** button controls the height of the platform, and is used in the nozzle height calibration procedure described on page 13.

The **Bottom** button returns the platform to the lowest position.

Set Nozzle Height
Takes whatever value you have in the **To** box and saves it as the Nozzle height to use during printing.

Stop All
Stops heating and all the movement of the printer. Once you click this button, the current model being printed is cancelled. You **CANNOT** resume a print job once the printer has been stopped. After you use the **Stop All** function, you will need to re-initialize the printer.

Pause Print
This button allows you to pause a print in mid-progress while allowing you to resume the print job where it left off. This is very useful if, for example, you want to change the material color mid-print. Another use for pausing a job mid-print is to allow fasteners to be inserted into printed cavities and then printed over to lock the fastener into place.

This option is only available when the printer is actively printing and above the first four printed layers.

Table Heat 1 hr
Click the **Table Heat 1 hr** button to heat the table to 105º C for a full hour.

Heating the platform will not take the full hour, but the longer the platform heats, the more the outer edges of the platform will be heated. For prints extending close to the edge of the platform, this will help prevent warping of the model during printing.

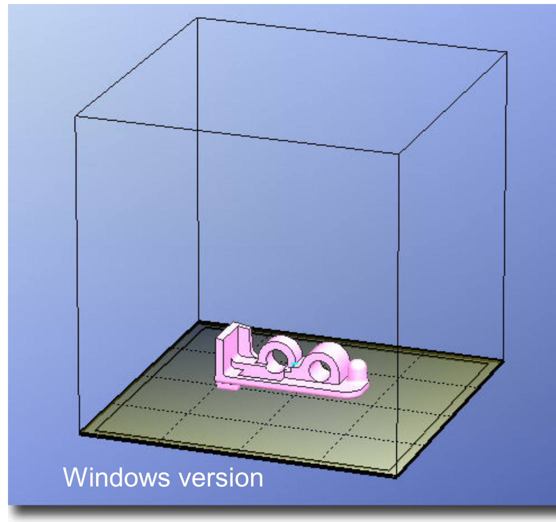
Note: You should always preheat the platform prior to printing to ensure the best results.

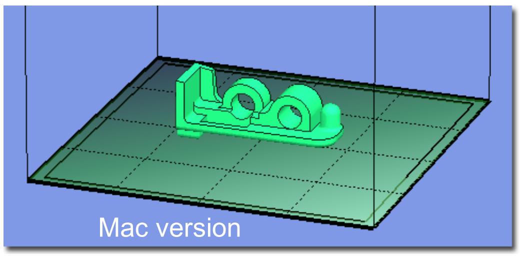
Stop Preheat (Windows) / Stop Heat (Mac)
This button will halt any heating of the table, either the 1 hour heat or the 15 minute preheat from the 3D Print menu. This option only appears when the table in actively being heated by one of these two operations.

Printing with the H-Series 3D Printer

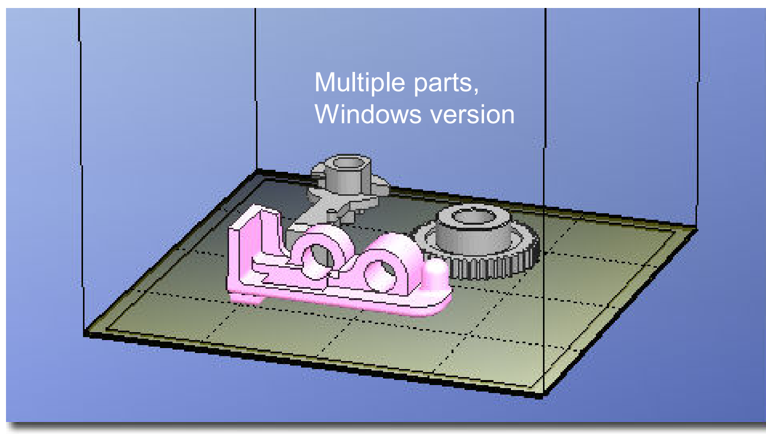
Loading a 3D Model

Click **File / Open** or the **Open** icon on the toolbar (Windows only) and select the model you want to open. The Afinia 3D Printer software only supports **STL** files (which is the standard input format for 3D printing files), the **UP3** and **UPP** formats.





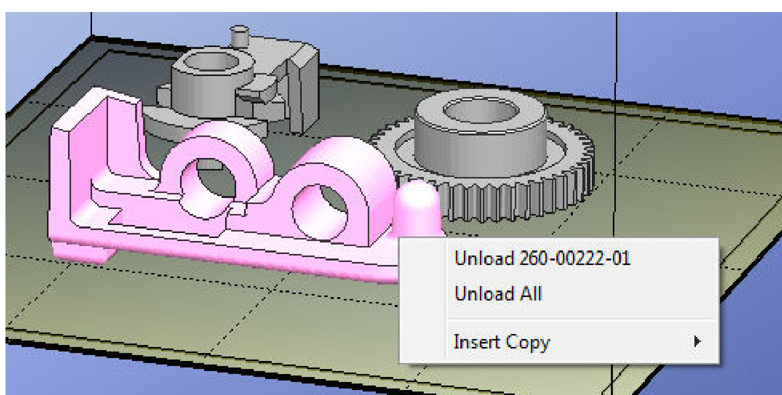
You can open several models and print them all at the same time. Simply repeat the open model procedure for each model you want to add (see ***Placing Models onto the Build Platform***, page 21, for more information).



Insert Copy

You can also add multiple copies of the same model to the platform by selecting **Insert Copy** from the right-click options (Windows) or by selecting **Copy** from the **Tools** menu. Select the number of copies from the list.

You will need to reposition the models after the copies have been added.



Unloading the Model, Windows

Click the left mouse button on the model to select it, and then click **Unload** on the toolbar, or click the right mouse button while over the model and a context menu will appear. Choose **Unload** using the model name or **Unload All** models if you have more than one file open and want to remove all of them.

Unloading the Model, Mac

Use either the **Unload** or **Unload All** button in the right tool pane. Click the **Unload** button to remove the currently selected model, or **Unload All** to clear all models from the workspace.

Saving the model

Choose the model and select **Save** from the **File** menu. The file is saved in UP3 format with the file size being 13%-18% of the original STL file size. This is a convenient format for users to archive or transfer files.

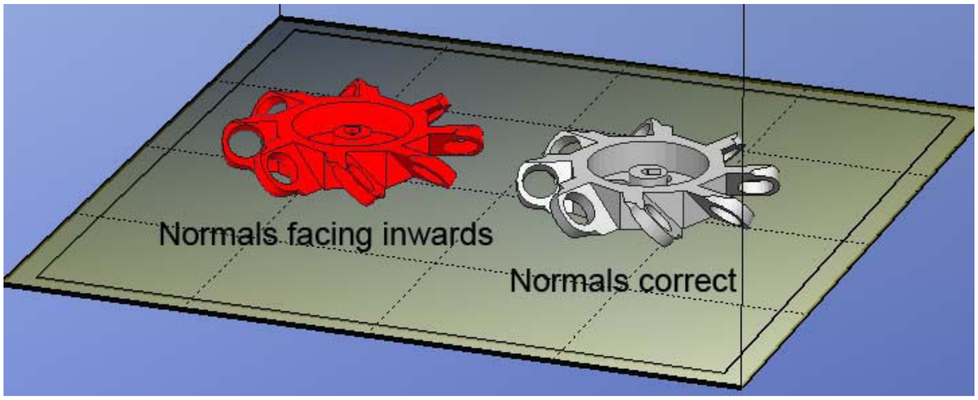
Saving the model as a project

Choose the model and select **Save As Project** from the **File** menu. All of the settings within the **Setup** or **Preferences** will be saved, as well as the **Quality** and **No Raft** settings. Along with the settings, the model itself is saved using the UP3 format.

The settings that are not saved within a project include the **Nozzle Height**, **UnSolid Model**, **Heat platform after finish**, and **Pause at** settings.

The project file will be saved with an extension of UPP. This one file can be copied to other locations or computers without needing to include the original STL file or files.

Note on STL files: For a model to print correctly, all the faces of the models need to have their normal facing outwards. The Afinia H-Series 3D Printer software uses model color to indicate whether a model is OK or not. The default color used by the software when opening a model is a light grey/pink color. If the normal are facing the wrong way, then the model is colored in red.

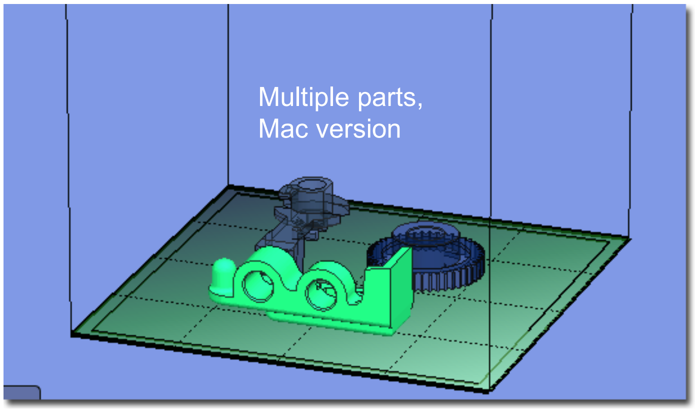


Fixing STL Files

The Afinia 3D Printer software includes a Fix option that attempts to fix any model that includes bad surfaces. Under the **Edit** menu in Windows you will see the **Fix** option, and under the **Tools** menu in Mac will be the **Autofix** option. Select the model with inverted surfaces, and click the **Fix** or **Autofix** option to attempt a repair of the bad surfaces.

Merging Models

If you have loaded more than one part onto the platform, you can combine them into a single file by using the **Merge** option from the **Edit** menu in Windows or the **Tools** menu in Mac. Simply open all the models you want to merge, arrange them the way you want on the platform, and click the **Merge** option. When you then save the file, all the components will be saved as a single UP3 file.



View Options

To observe the target model in different ways, use the mouse to control the view.

Rotate

Press the middle mouse button and move the mouse. The view can be rotated and observed from different angles.

Pan

Press Ctrl and the middle mouse button at the same time and move the mouse. This causes the view to pan. You can also use the arrow keys to pan the view.

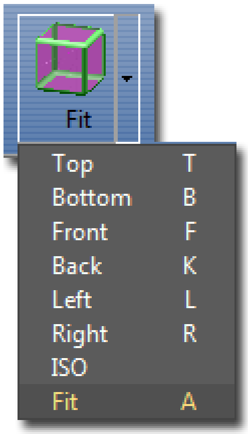
Scale

Rotate the mouse wheel. The view will zoom in or out.

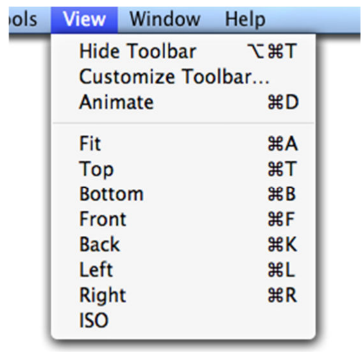
View

The system has eight preset standard views available, with the default view being **Fit**. Click the **View** button on the toolbar (Windows) or the **View** menu to select the View options.

After selecting an option, the caption under the View button will show the selected view name.



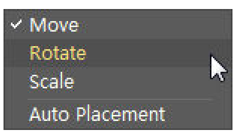
Windows version

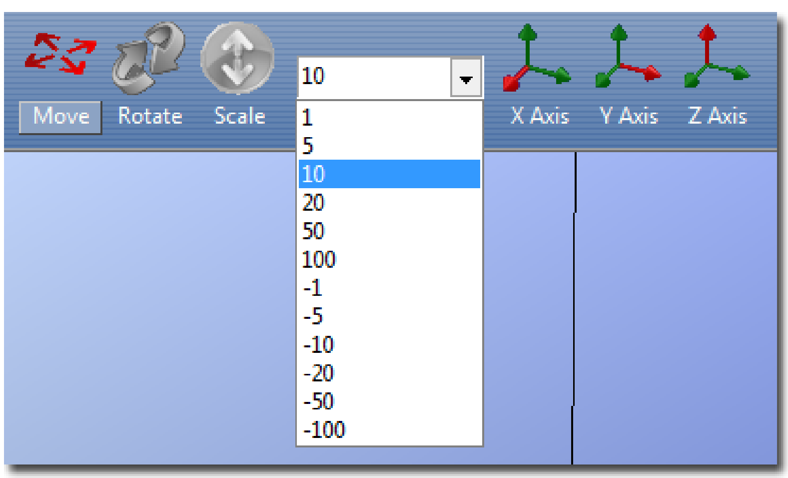


Mac version

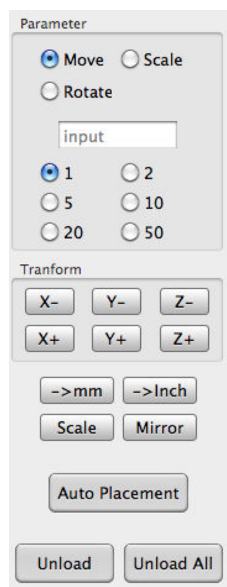
Model transformations

Model Transformation can be achieved through the Edit menu or the toolbar:





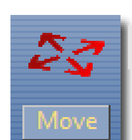
Windows version



Mac version

Moving the Model

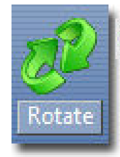
Click the **Move** button and choose or input the distance you want to move into the text box. Then choose the axis (direction) in which you want to move. Each time you click the axis button the model will move again.



For example: To move the model -5mm along Z axis (or down 5mm):

Windows	Mac
1. Click **Move** 2. Input **-5** in the text box 3. Click the **Z axis** button 	1. Select the **Move** option 2. Input **5** in the text box 3. Click the **Z-** button 

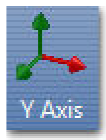
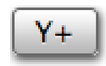
Windows TIP: If you hold down the **Ctrl** key, you can drag the model to a position.



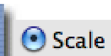
Rotating the Model

Click the **Rotate** button on the toolbar, choose or input how many degrees you want to rotate in the text box, and then choose the axis of rotation.

For example: To rotate the model around Y axis by 30°.

Windows	Mac
1. Click **Rotate** 2. Input **30** in the text box 3. Click the **Y axis** button 	1. Select the **Rotate** option 2. Input **30** in the text box 3. Click the **Y+** button. 

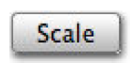
Positive numbers rotate the model counterclockwise; negative numbers rotate the model clockwise.



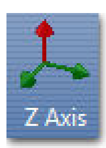
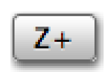
Scaling the Model

Click the **Scale** button on the toolbar, choose or input a scaling factor in the text box, and then scale the model uniformly by applying that scaling factor. If you only want to scale along one axis, click the axis around which you want the change to be applied.

Example 1: Scale up the model uniformly by 2.0 times.

Windows	Mac
1. Click **Scale** 2. Input **2.0** in the text box 3. Click the **Scale** button 	1. Select the **Scale** option 2. Input **2.0** in the text box 3. Click the **Scale** button 

Example 2: Scale up the model by 1.2 times along the Z axis only.

Windows	Mac
1. Click **Scale** 2. Input **1.2** in the text box 3. Click the **Z Axis** button 	1. Select the **Scale** option 2. Input **1.2** in the text box 3. Click the **Z+** button 

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Example 3: Scaling to convert inches to mm.

Occasionally an stl file may appear much smaller or much larger than designed. This is due to the design software saving the units of measure as inches rather than millimeters; the Afinia 3D software uses millimeters only, so a 1 inch model would appear as 1 millimeter.

This is simple to resolve using the following steps:

Windows	Mac
1. Click **Scale** 2. Select or input **25.4** in the text box 3. Click the **Scale** button  	1. Select the **Scale** option 2. Input **25.4** in the text box 3. Click the **Scale** button 

Conversely, if the model initially appears much too large, you can convert the size from millimeters to inches by selecting (PC only) or entering **0.03937** into the text box and clicking the **Scale** button.

This does not actually convert the models measurements, just scales it in the selected direction.

Placing Models onto the Build Platform

Appropriately placing your models on the platform can have an effect on print quality.

TIP: In general, try to place your model in the center of the platform.

Auto Place

Click the **Auto Place** button, on the far right of the toolbar, to automatically place the model on the platform. When there is more than one model on the platform, using Auto Place is recommended.

Windows TIP: Check the **Auto Place** option in the **File** menu to automatically position the model on the platform when the model file is opened.

By Hand (Windows)

Press the **Ctrl** key and choose the target model by pressing and holding the left mouse button. Move the mouse and drag the model to the desired position.

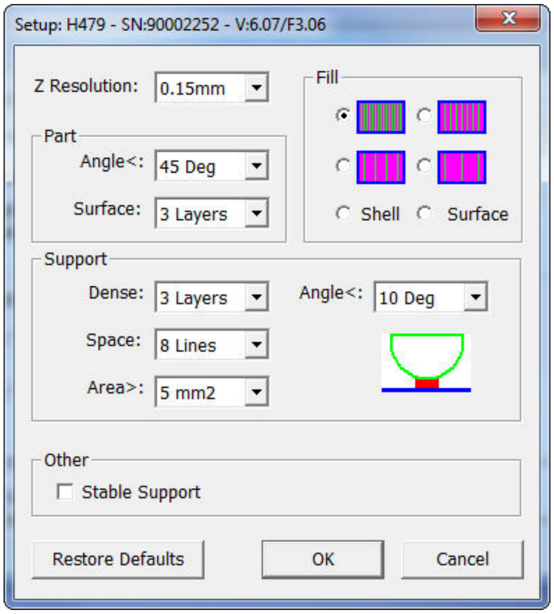
Using the Move button

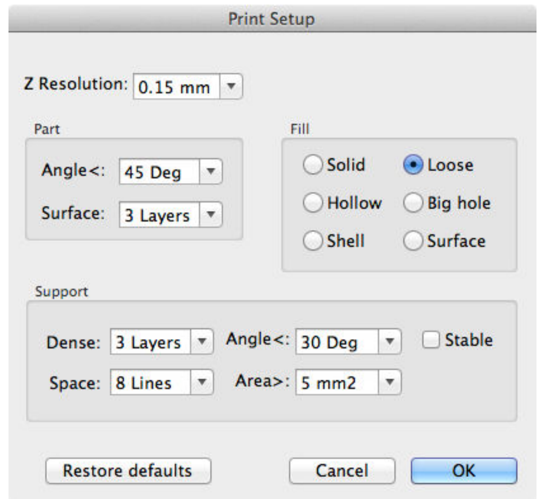
Click the **Move** button (Windows) or the **Move** parameter (Mac) on the toolbar, choose or input the distance in the text box, and then choose the axis for the direction in which you want to move.

NOTE: When more than one model is open, the gap between each model should be kept to at least 12mm to prevent the models sticking together.

Print Setup Options

Click the **Setup** option in the **3D Print** menu or the **Preferences** button on the **Print** and **Print Preview** windows. The following dialog box will appear:





Mac version

Windows version

Print Settings

Z Resolution

This setting specifies the print resolution or layer thickness of the printer. Options are **0.15mm** to **0.40mm** per layer, in 0.05mm increments, with the most current Printer ROM version applied.

Part Settings

Angle

The Part Angle sets the horizontal printing orientation for fill printing. Set at **45 Deg**, the part will be filled in with material printed at 45 degrees to the X- and Y-axes. Changing the value will change the print angle to that selected, with the angle of each layer still being printed perpendicular to the one below.

The orientation of the part itself will not be changed, just the angle at which the fill material is printed. This setting will also not change how the perimeter of the model is printed.

Surface

This setting determines how many layers form the bottom face of a part when it is not solid. For example, if you set it to **3**, the machine will print 3 complete layers before going into non-solid mode.

This does not affect the side wall thickness on non-solid parts, which are all the same thickness (approximately 1.5mm) regardless of the fill mode.

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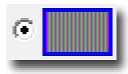
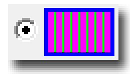
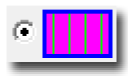
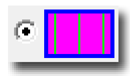
Fill Settings

There are four ways to fill the interior of the parts, as described below.

The part is nearly solid plastic, giving you the strongest structure. This Fill setting is recommended for functional engineering parts. Mac setting: **Solid** 	The interior of the part is filled with a reasonably small scaffold structure. This is the default Fill setting.  Mac setting: **Loose**
Mac setting: **Hollow**  The interior of the part is filled with a medium spaced scaffold structure.	 Mac setting: **Big Hole** The interior of the part is filled with a large spaced scaffold structure, using the least amount of material.

Shell

Selecting the **Shell** setting will allow you to print a solid part as hollow by removing the fill material regardless of the Fill setting.

For example, when printing a sphere 4cm in diameter at **0.15mm** resolution, the most open fill setting, and the rest of the settings at the default values will use 9.3 grams of filament and print in 61 minutes. Checking the Shell setting will reduce the material use to 5.4 grams and print time to 36 minutes by not printing the fill material.

Some models may not be suited to printing with the Shell setting checked.

This will not affect the printed model's wall thickness or support material requirements.

Surface

Selecting the **Surface** setting will allow you to print a model as a single-layer outline of the model perimeter. Note that this setting will not work with models having a base, solid top, or requiring any inner fill structure.

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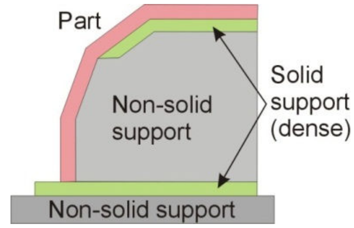
Support Settings

Dense

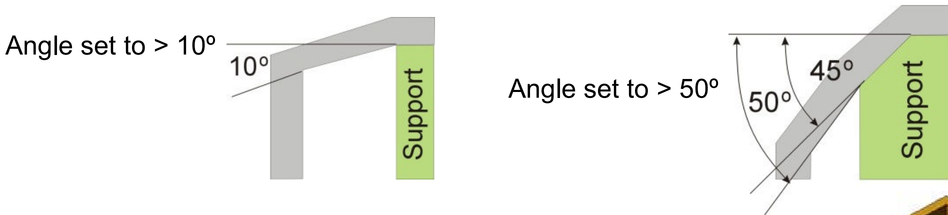
This represents how many layers of dense support material is printed directly beneath the model. The greater the number of dense support layers, the more stable the print will be but the support will be more difficult to remove.



Angle

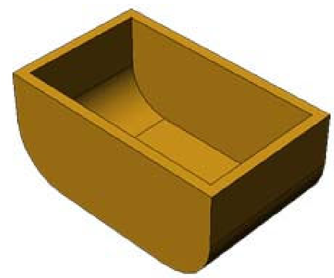
The Support Angle setting specifies the maximum Angle at which support material will be printed. If the angle from horizontal is smaller than the selected setting, the printer will add solid support layers under the part surface.

For example, if the setting is **10 Deg**, only surfaces that are within 10 degrees from horizontal will be printed with support material to hold them up. Increasing the setting to **50 Deg** will result in support material being printed for surfaces that are within 50 degrees from horizontal.

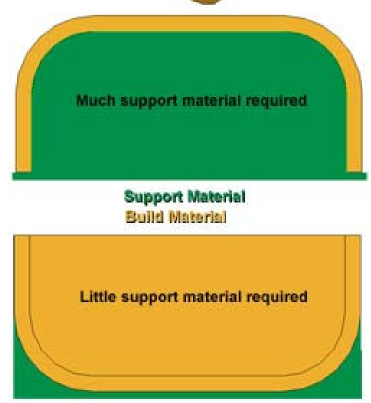


Increasing this value will add more material and time to the print. Decreasing this value may result in poor printing of overhanging surfaces.

There is a balance between minimizing the amount of support material and maintaining the quality of the part, as well as minimizing the difficulty of removing support material.



The orientation of the part on the print platform is critical in determining both how much support material gets used and how difficult the support material will be to remove.



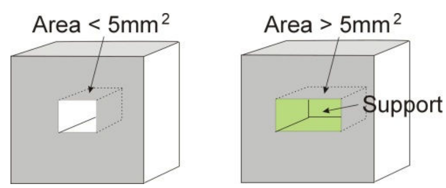
As a general rule, it is easier to remove support material from the outside of a part than from the inside. As can be seen in the picture to the right, the part would use a lot more support material if printed with the opening facing downwards than if it were facing upwards.

Space

This setting specifies the distance between the lines of non-solid support material. Changing this parameter changes the balance between the quantity of support material used, ease of support material removal, and part print quality. Only advanced users should change the Space setting.

Area

This setting specifies the surface area above which support material is printed. When you choose **5 mm^2**, for example, there will be no support if the overhanging area is less than 5mm^2. While a little material is saved and a slightly faster print speed is achieved when this setting is increased, the stability of the part may be reduced during printing.



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Two special options for the Support Area setting are available. The **Only Base** setting will use a minimum of support material. In many cases, no support material other than that needed to support the base of the model will be used. The **0 mm^2** setting will create support material when the Angle criterion is met regardless of the surface area.

Other Settings

Stable Support

Stable support creates support that is more solid, and the model is less likely to distort, but the support material will be more difficult to remove. This can be useful where tall, narrow support is needed

TIP: All setup and configuration settings aside from the Nozzle Height Calibration and Platform Leveling parameters are stored in the software, not on the Afinia H-Series 3D Printer. If you move the printer to a different computer, you will need to repeat all the calibration and setup procedures.

Printing

TIP: One of the keys to successful printing on the Afinia H-Series 3D Printer is **platform preparation** and **preheating**. Particularly with large parts, there is a tendency for the edges of the part to lift from the platform (which can be a little colder than the center) and cause the parts to warp. The best results will be achieved if:

- The platform is perfectly level and calibrated
- The nozzle height is correctly set
- The printer is being run in a room that is not too cold (warmer than 65° F) and free of drafts
- **The platform is very well preheated**

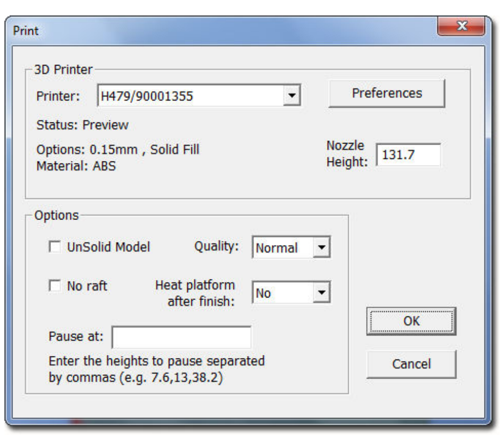
Please ensure the following points are taken care of before printing:

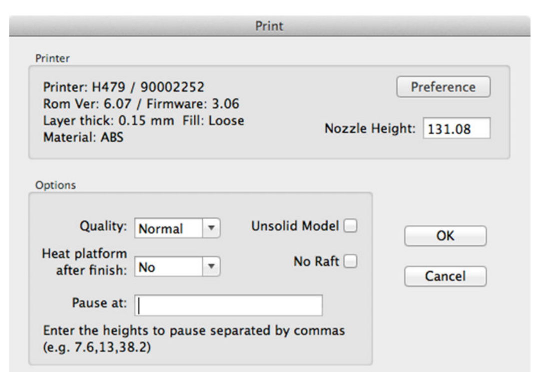
Connect the 3D printer, initialize it, and set up the printing system. Load the model and place it properly on the virtual platform of the software window. Check if there is enough material for the model (use the Print Preview to calculate the required material, or the software will tell you if there is not enough material when you begin the print). If not, change the spool to a new one.

For most surface preparations, it is recommended that you preheat the build platform. Click the **Table Preheat 15 mins** option in the **3D Print** menu or click the **Table Heat 1 hr** in the **Maintenance** window to preheat the platform.

Let the platform heat to at least 90° C when printing with ABS before beginning the print. Select Maintenance from the 3D Print menu to monitor the platform and nozzle temperatures.

Click **Print** from the **3D Print** menu.





Print Options

Nozzle Height

You can make changes to the Nozzle Height using this setting, but it is not recommended unless you know that the value you are entering in is correct.

If the nozzle is too far from the platform during printing, the material may not adhere correctly to either the platform or to the previous layer.

If the nozzle height is set too high, the platform can raise up into contact with the nozzle itself, potentially damaging the nozzle.

It is recommended that you use the **Calibrate Nozzle Height** process as listed on page 13 to make any changes rather than in the Print dialog.

Quality

Options are **Normal**, **Fast**, or **Fine**. This setting determines the speed at which the printer moves. As a general rule, the slower you print the better the quality of the parts, although there are exceptions to this rule.

For tall parts, running at **Fast** speed can be problematic as the printer can vibrate to the extent that print quality is affected.

For large surface area parts, the **Fine** setting can be problematic as the part takes longer to print and the corners of the raft are more likely to lift from the platform.

UnSolid Model

This function is useful for printing STL files that are not perfect. A perfect STL file is a fully enclosed surface, with no holes in the surface skin, and no overlapping surfaces. If your file is not perfect, this option should allow you to print it anyway.

The software will auto-detect models that may require this setting and check this option. You can manually remove the check to de-select this function if needed.

No Raft

While you can choose to skip the Raft with this option, it is not recommended. The raft adds stability to the adhesion between the part as it is printing and the platform.

Additionally, the **Platform Calibrate** feature (see page 14) which can compensate for an uneven print surface will be bypassed if the raft is not printed.

Heat Platform after finish

Checking this option will keep the platform temperature at a higher level after printing is complete. This can make it easier to remove the model from the platform, depending on the platform preparation, or keep the platform heated to begin your next print more quickly.

Pause At

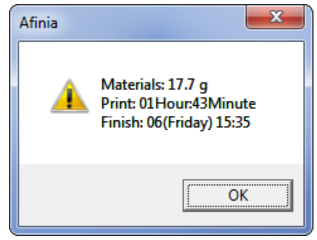
You can use this option to automatically pause the printer at specific heights during the printing process. This can be useful if you will be changing filament or inserting a non-printed part at a specific point during the printing of the model. Multiple heights can be entered into the setting, separated by commas. The height uses millimeters as the scale.

For instance, entering **13.5, 20, 27.25** will automatically pause the printing when it has reached 13.5 millimeters, 20 millimeters, and 27.25 millimeters.

The height is based on the model only. If you are printing with a raft, you do not need to add the height of the raft to the numbers you add in; the software will do so for you.

Once the print has auto-paused, open the Maintenance window to perform the **Withdraw**, **Extrude**, and **Resume Print** functions.

Calculating model costs



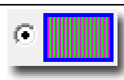
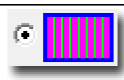
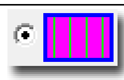
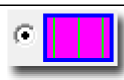
The easiest way to calculate the cost of the material that will be used for your model is to use the **Print Preview** option under the **3D Print** menu. The application will calculate the total weight of material used, including the raft and any support material.

Use the weight from the Print Preview to determine the cost to print the model using the following formula:

$$\textbf{Cost to Print} = \textbf{Weight of Model X} \left(\frac{\textbf{Cost of Spool}}{\textbf{Full Filament Weight}} \right)$$

Use the full weight of the filament that you purchased, not the current weight of the spool. For instance, if you purchased a 700g spool of Afinia Premium ABS filament, you would divide the cost of the spool by 700g to get the cost per gram of material.

The main factors that affect model cost are the **Fill** and **Support** settings. For example, you are printing a cube measuring 30mm x 30mm x 30mm with a layer thickness of 0.15mm. With the Support settings left at their default values, the following quantities of material will be used for each of the four **Fill** settings:

PC Fill Setting	Mac Fill Setting	Fill Percentage	Weight of Model
	Solid	50%	17.7 g
	Loose	25%	12.0 g
	Hollow	17%	9.1 g
	Big hole	12%	8.2 g

Note: Shell and Surface fill settings results are not shown, as the model used is not one that would print well in either mode due to the horizontal surfaces.

In this example, the model printed at the lowest density Fill setting will be about half the cost as printing it at the highest density Fill setting, but this may not apply to all models. Each model will have a different relationship between the amount of material used and the Fill and Support settings. Always run a Print Preview if you are calculating the printing costs of any given model.

TIP: Once the print has started, you can unplug the USB connection between the computer and the printer. The print job is stored in the printer's internal memory, so the computer is no longer required. If you need to interact with the printer during the print (paused printing, for instance), you will need to reconnect the printer to the computer.

Save as Project

Once you have all the parts on the platform and the print settings the way you want them, you can use the **Save as Project** option under the **3D Print** menu to create a 3D print project. All of the settings within the **Setup** or **Preferences** will be saved, as well as the **Quality** and **No Raft** settings. Along with the settings, the model itself is saved using the UP3 format.

The settings that are not saved within a project include the **Nozzle Height**, **UnSolid Model**, **Heat platform after finish**, and **Pause at** settings.

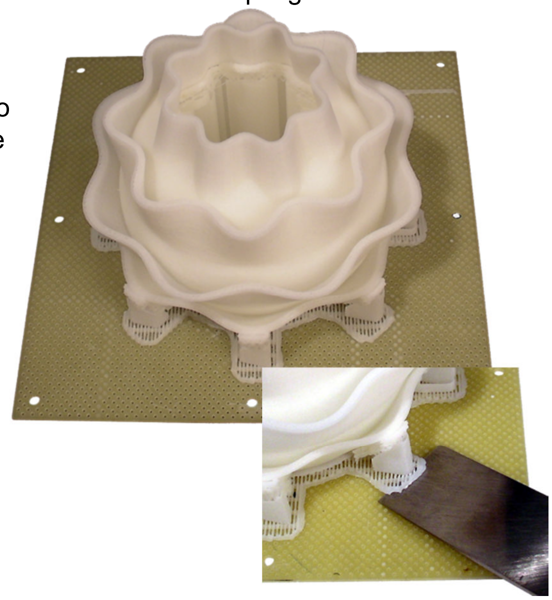
The project file will be saved with an extension of UPP. This one file can be copied to other locations or computers without needing to include the original STL file or files.

Model Removal

When the model has finished printing, the printer will beep, the nozzle and platform will stop heating, and the printer platform will lower.

It is very strongly recommended that you never attempt to remove the finished model from the platform while in the printer. If you do, you may bend the entire platform assembly so that it is no longer perpendicular to the printer head or affect the platform leveling.

If your print surface is attached directly to the printer platform, detach the printer platform from the printer by removing the 2 screws at the bottom of the platform before attempting to remove the model.



If you are using any method that clips another surface to the printer platform, simply remove the clips holding the surface to the platform and remove the entire surface.

Removal from FR-4 (Perf) Board

Gently slide a spatula or chisel under the model and slowly wiggle it back and forth to lift the support material from the print surface.

Remember to use gloves as the board and model may still be hot and to prevent injury from any tool being used to help release the model from the FR-4 Board.

Removal from Borofloat Glass

After removing the glass from the printer platform, allow the glass to cool completely. As the glass cools, you may hear audible cracking sounds – this is the ABS film contracting and detaching from the surface of the glass.

If the model does not release completely from the surface of the glass, spray a small amount of an ammonia-based window cleaner onto the surface of the glass near the edge of the model. After a few moments, the model should release.

With the glass surface, you will need to reapply the ABS film after removing each print job.

TIP: Depending on the platform preparation method you are using, the model may be easier to remove from the printer when it is still hot. If you want to heat the platform before removing your model, use the **Table Heat** option from the **3D Print** menu.

	CAUTION: It is strongly recommended that you do not attempt to remove the model from the platform while the platform is still attached to the printer. Doing so may damage the printer or affect the platform level and nozzle height calibration.
	GLOVES: It is recommended that gloves be worn as the platform may still be hot and to prevent injury from any tool being used to help remove the model from the platform.

Removing Support Material

Printed models are composed of two parts. One part is the model itself, and the other part is the support material used to support any overhanging parts of the model.

The support material is the same physical material as the model material, but printed at a much lower density. Support material is very easy to distinguish from the model material, making it is easier to remove.

The left picture above shows the teapot with its support material still attached, while the right picture shows the teapot with support material removed.

The support material can be removed using a combination of tools. Some material can easily be removed by hand. Support material close to the model is easier to remove using tools such as wood carving chisels, long nose pliers, or wire cutters.

GLOVES/SAFETY GLASSES: The support material and the tools are sharp. Wear gloves and safety glasses when removing the part from the printer.

ALWAYS WEAR GLOVES AND SAFETY GLASSES WHEN REMOVING THE SUPPORT MATERIAL!

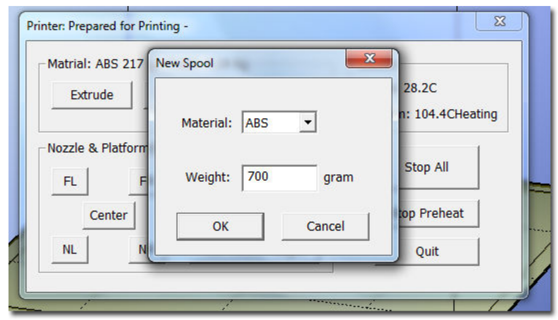
Maintenance

Changing the Material

First withdraw the leftover material from the printer. Initialize the printer and choose **Maintenance** from the **3D Print** menu. Click the **Withdraw** button and the nozzle will start to heat. When the nozzle reaches the correct temperature, the printer will beep and you can gently withdraw the material.

Once the old filament has been removed, place a new spool of material on the spool holder and pull the filament through the slot in the top of the holder. Feed the filament through the filament tube until the material is about 10cm out of the tube. Insert the end of the filament into the hole at the top of the extruder head.

Before extruding the new filament, use the **New Spool** function to set the temperature to the selected filament type and to help the sprinter keep track of the amount of filament that is available using the **Material** and **Weight** settings, respectively.

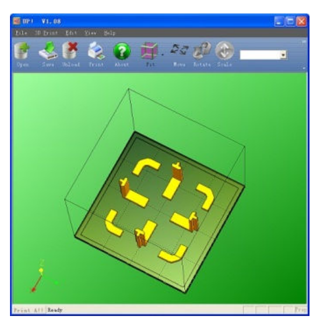


Click the **Extrude** button. After the printer nozzle has warmed up to the correct temperature, the printer will beep. Gently push the filament into the hole at the top of the extruder head with a little downward pressure until the extruder mechanism starts to feed the filament through on its own.

TIP: If you are loading a different color filament than the last spool, run the **Extrude** function a few times immediately after the new spool is in place. This will help extrude out any remaining filament material of the previous color.

	CAUTION: If the nozzle is blocked, remove the nozzle and clean it.
	GLOVES: The extruder and platform are hot. Use gloves when working in this area of printer.

Vertical Calibration



The Vertical calibration procedure allows you to ensure that the printer platform is perfectly horizontal and that the printer prints consistently in the X, Y, and Z directions.

First, print the supplied Calibration model on your printer at the scale of the part when initially opened. The calibration file is in ***C:\Program Files\Afinia\Example*** on PCs and in the ***Afinia*** directory off the root of the main drive on Macs.

After the calibration model is printed, remove the platform ***without removing the parts.***

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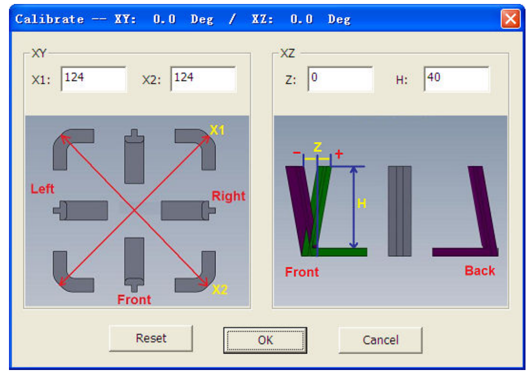


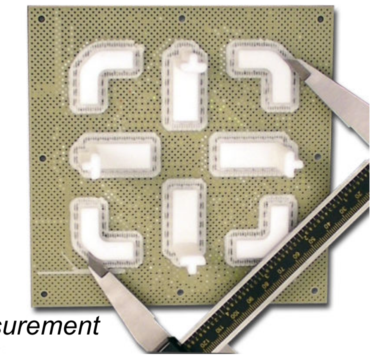
Open the **Calibrate** dialog from the **3D Print** menu. Measure the X1 and X2 length, as shown in the pictures below.

IMPORTANT NOTE: Before you enter any new calibration values, always click the **Reset** button, otherwise the new values get added to the old ones. Before you enter any new values, the bar at the very top of the screen should read: XY: 0.00 deg / XZ: 0.00 deg.

Measure the calibration print from front left to rear right corners of the printed parts on the platform to determine the **X1** measurement, and the rear left to front right to determine the **X2** measurement.

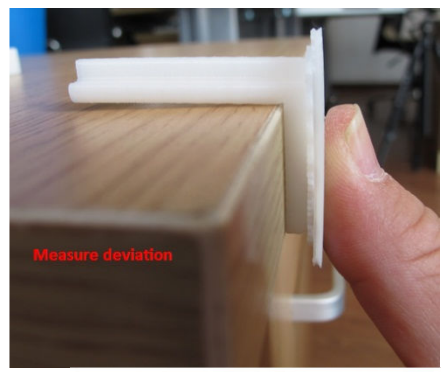
Be sure that you are not including the raft or support material when taking these measurements!

Enter the measured **X1** and **X2** values into the appropriate boxes.

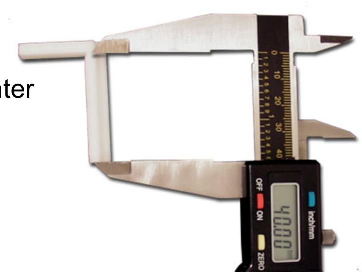


Checking the X1 Measurement

Next, carefully remove the Front Center 'L' shaped component from the platform and check the inside angle. If it is not 90º, measure the exact distance in millimeters that the end of the long arm of the part would need to move to get the angle to be 90º and enter that distance into the Z box. If the angle is less than 90º, the value to be put into the Z box will be a positive value. If the angle is more than 90º, the value to put into the Z box will be a negative value. For example, if the end of the long arm is 1.3 mm above the surface, enter **-1.3** in the **Z** box.



Finally, measure the long arm of the Front Center component from the inside of the angle to the end, which should be 40mm at full scale. Enter the exact measured value into the **H** box of the **Calibrate** dialog box.



Click **OK** to record all these values and exit the calibration window.

Cleaning the nozzle

After a lot of printing, the nozzle may be covered with a layer of oxidized filament material. When the printer is printing, this oxidized material may melt on the nozzle, and may create discolored spots in the model or even clog the nozzle. To avoid this you need to regularly clean the nozzle.

Preheat the nozzle as the first step in order to melt the oxidized filament. Click the **To Bottom** button on the **Maintenance** dialog box, and then click the **Extrude** button. Wait until the material is finished extruding, then remove any extruded filament from the nozzle.

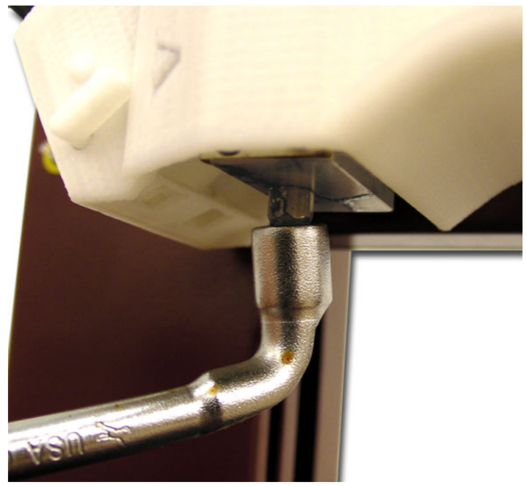
Use a heat-resistant material such as 100 percent cotton cloth or soft paper and a pair of pliers. With the material between the pliers and the nozzle, apply gentle pressure with the pliers and turn the pliers to remove the oxidized filament material. **Do not apply heavy pressure!**

Remember, the nozzle heats up to 260° C (500° F) – that's over two and a half times the boiling point of water. **Do not touch the nozzle or nozzle mount with bare skin during this process!**

If this does not clear up any issues, you should try removing and soaking the nozzle in acetone overnight to remove excess ABS material from the nozzle. Ultrasonic cleaning baths also work.

Removing / Changing the Nozzle

If the nozzle becomes blocked, you may need to remove it in order to unblock or change it altogether.



To remove the nozzle, use the **Withdraw** button on the Maintenance dialog box to remove as much filament from the nozzle as possible. Once the Withdraw has completed and before the heater has a chance to cool below 200° C, use the nozzle wrench provided in the toolkit that comes with your Afinia H-Series 3D Printer.

Use the same process to replace the nozzle, being sure to heat the extruder to at least 200° C before tightening the nozzle back down.

Do not apply too much torque to the nozzle to avoid twisting the heater assembly!

TIP: Heating the nozzle will make it easier to remove and replace.

⚠	WARNING: Be careful when handling the heated nozzle and nozzle wrench once the nozzle has been removed!

Cleaning the Platform

Regardless of the method of preparing the platform that you have chosen, a smooth surface will improve your results.

- If you are using the FR-4 Board as the print surface, you should remove any remaining filament material from the surface of the board before printing again.
- If you are using blue painter's tape on the platform, you will need to replace the tape once it becomes uneven. You may need to remove excess adhesive from the platform during the process of replacing the tape.

Lubrication of bearings

The 3 axial bearings on the Afinia H-Series 3D Printer may occasionally require a bit of lubrication to keep it operating smoothly. The recommended grease to use is lithium grease.

When lubricating the bearings, first clean off as much old grease as possible from the bearings before applying new grease to the bearing. Slide the platform several times in the appropriate direction to spread the grease evenly.

If you have any questions about lubricating the bearings, please contact Technical Support (see page 36 for contact information).

Spare parts

Most of the plastic parts on the printer can be printed by the Afinia H-Series 3D Printer itself. If you need spare parts for your printer, the files for the printable parts can be found in the ***C:\Program Files\Afinia\Example\Spare Part*** folder on PCs and in the ***Afinia*** directory off the root of the main drive on Macs.

Tips & Tricks

Preheat the platform before printing

Large parts can sometimes have their corners lift from the platform, which causes the part to distort. This is caused by uneven heat across the surface of the platform.

Preheating the platform (see page 26) to at least 90 degrees C when printing with ABS is a step you don't want to miss. Having the platform heated before print starts helps ensure that the model will remain adhered to the platform during printing.

You can monitor the platform temperature in the **Maintenance** window.

Level Platform and Correct Nozzle Height

One key to both successful printing and removal of the print raft is to make sure the platform is level and that the nozzle height is set correctly. Use the **Maintenance** window to bring the nozzle close to the print surface, then the **Platform Calibration** utility to level the platform and set the nozzle height (see pages 13-14).

Be sure to use the calibration utility to help compensate for any parts of the print surface that aren't level!

Position the parts as close to the center of the platform as possible

The center of the platform is where the heating is most regulated, which helps to keep the support raft adhered to the platform. Try to avoid printing any object near the edges of the platform.

Model Orientation Tips

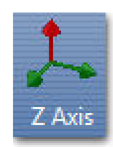
Generally, follow these three simple tips on model orientation for better print results:

a) Position the model so the largest flat surface is on the bottom
b) If your model has any cylindrical parts (either solid or holes), position them so they are vertical
c) Minimize support material by orienting the model with as many concave surfaces up as possible

Remember, these tips may not be able to be applicable to all models. Each model is unique and each has the best orientation for printing.

Scaling your Model

Not only can the Afinia 3D software scale your model in all three dimensions, you can use the Scale function to change the size in any one of the three dimensions independently. For instance, you can make your model taller by setting the scale factor and clicking just the Z Axis button without affecting the width or depth (see page 21).



Merging and Rafts

Positioning multiple models too closely in the software can result in overlapping rafts, which can lead to printing failure. If you do change the model positions once they've been positioned automatically, use the **Merge** function in the **Edit** menu before printing to have the software eliminate that problem by creating a single raft where they may be overlapping.

Be sure to save these merged models if you will be regularly printing them as a group!

Minimal Support Material Use

The latest versions of the Afinia 3D Software includes a feature that allows you to avoid most support material. When specifying the Print Preferences, select **Only Base** for the **Support Area** setting (see page 25-26).

Support material around the bottom of the model will still be generated, but the amount of support material will be greatly reduced.

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Shell Setting Tips

The **Shell** option for the print **Fill** setting can be used to create truly hollow prints, saving time and material. However, not all models can be printed with this fill setting.

Models with relatively small horizontal or near-horizontal surfaces are potential candidates for shell printing, as these surfaces require little or no internal support to be successfully printed. Remember, each model is different – you may need to experiment with each model to find out if it can be used with **Shell** printing.

Decrease print time where possible

The faster you can print parts, the less lifting from the platform you are likely to get. Some ways to increase print quality include:

- If possible, try to avoid printing large parts in solid mode
- Set the layer resolution to as large a value as possible while still retaining the quality needed for the finished part
- Print the part in **Normal** or **Fast** mode
- If printing multiple parts at once, reduce the number of parts that are being printed

Pause During Print: Changing Filament

If you need to change the filament during printing, you can either use the **Pause Print** button in the **Maintenance** window or enter in automatic pauses when you are setting up the print parameters (see page 27).

When paused, click the **Withdraw** button to remove the current filament. After changing filaments, insert the new filament and click the **Extrude** button to load your new filament.

If you have changed colors, you may need to extrude a few times to remove the last of the previous filament color.

Keep the extruded filament connected to the nozzle – pull it from the nozzle just before the nozzle contacts the print surface when resuming the print to keep any stray strands from sticking to your model.

Model Creation: What does "Manifold" mean?

For any model to print correctly, it should be a manifold object. What this means is, as simply as possible, is that each edge must be in contact with two and only two surfaces. Most design software will allow you to create non-manifold objects, which can result in print problems.

The most common way for a model to become non-manifold is when several objects are joined together, creating surfaces in the model that are in contact with or crossing through each other.

The **Fix** function in the **Edit** menu of the Afinia 3D software may repair the non-manifold problem areas, but the best solution is to correct any problems in your design software. Many software packages have functions to check for and repair any non-manifold models – the documentation for your software should be consulted.

Model Creation: What does "Surface Normalization" mean?

The outer layer of every 3D printed object is actually composed of an outer surface and an inner surface. Surface Normalization means these surfaces are pointing the correct way. If you have an outer surface buried inside your model, or have an inner surface on the outside of the model, you will need to normalize the surfaces.

The most common way for non-normalized surfaces to appear is when two surfaces cross each other in the model.

The **Fix** function in the **Edit** menu of the Afinia 3D software may resolve the surface problems, but the best solution is to correct any problems in your design software. Many software packages have functions to check for and remove any non-normalized surfaces – the documentation for your software should be consulted.

Status Indicator

The table below explains what each Status Indicator state means.

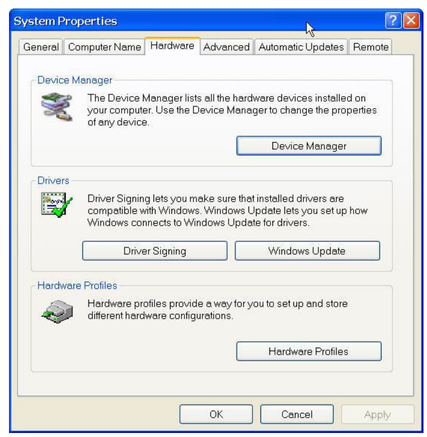
LED State	Indicates:
Solid Red	Printer is not initialized; initialize printer either using the software or the initialize button on the front.
Solid Green	Printer is Ready
Flashing 10 times per second	Data is transferring to printer
Flashing 5 times per second	1. Extruder is heating ***or*** 2. Extrude or Withdraw Material function in progress
Flashing about 2 times per second	Printing in progress
Flashing about every 2 seconds	Printing has stopped
Rapid strobing between green and red	Printer is in an error state; power cycle and re-initialize the printer

Troubleshooting

Problem or Error message	Solution
No power	Verify power cord is securely plugged in
Extruder or platform fails to reach operating temperature	Verify printer has initialized. If not, initialize the printer (see page 11)
	Heater is damaged. Contact Technical Support (page 38)
Material not extruding	Material is stuck in the extruder; remove the material (see page 31)
	The nozzle is clogged and needs to be cleaned (see page 32) or changed (see page 33)
Cannot communicate with printer	Printer not initialized; use Initialize button on front or Initialize function in software
	Make sure the USB cable is connected to the printer, and to the PC
	Unplug the USB cable, then plug in again
	Reset the printer—power off then power on
	Restart the PC
Others	Contact Technical Support (see page 38)

Solution for "Winusb.dll not found" problem (Windows)

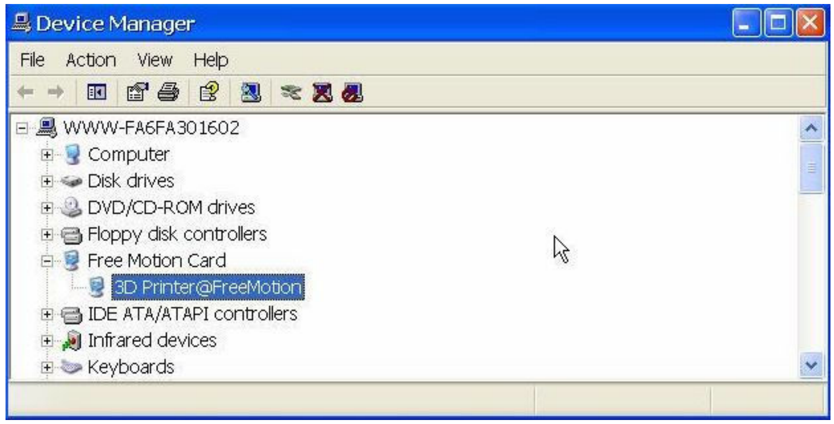
If you encounter a "Winusb.dll not found" error message, please follow the steps below:



Option 1: Uninstall Older Driver and Auto-Install New Driver

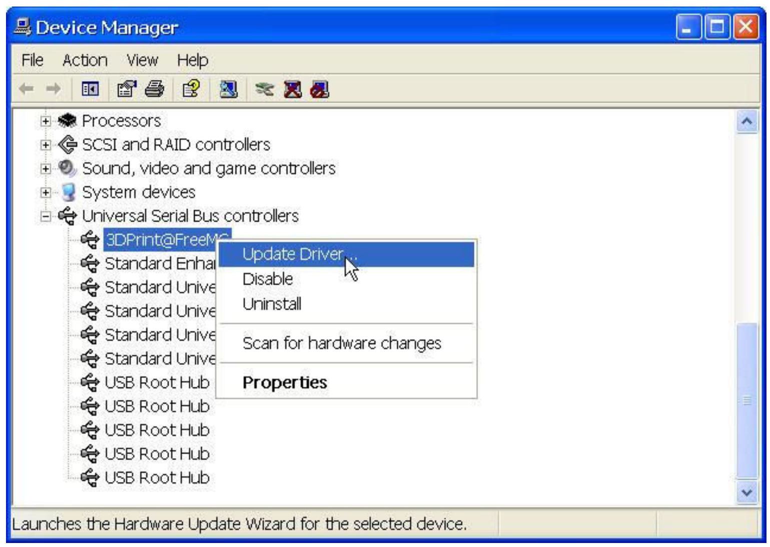
1. Open the Windows control panel, go to the **System Properties** dialog box and select the **Hardware** tab.
2. Click the **Device Manager** button, and the following dialog box will popup. Find the **3DPrinter@FreeMC** in the USB section.
3. Click the right mouse button and select the **Uninstall** option. The confirm dialog box will appear. Click **OK**.
4. Install the latest Afinia H-Series 3D software.
5. Unplug the USB cable, then plug it back in. Windows will find a new device. Manually select the driver folder (the default location is **C:\Program Files\Afinia\Afinia 3D Printer\Drivers**).

6. There should now be a new driver section in the device manager as shown to the right.



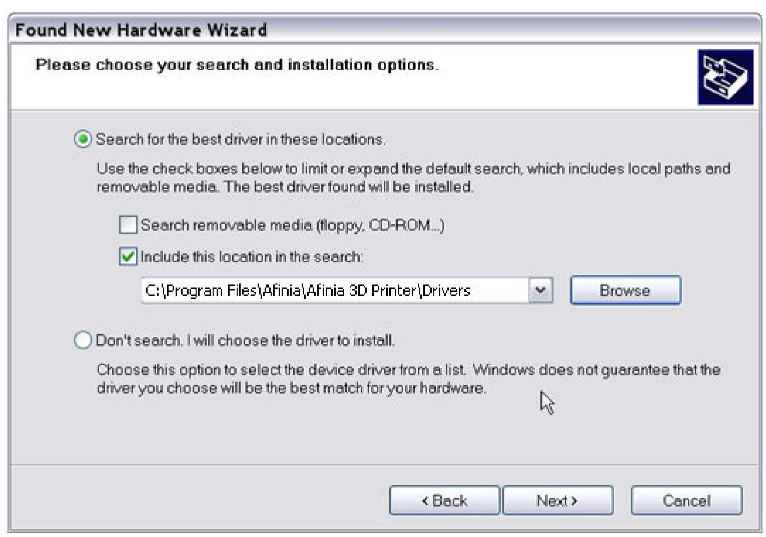
Option 2: Update the driver manually

1. Install the latest Afinia H-Series 3D Printer software.



2. Find the **3DPrint@FreeMC** driver in the **Device Manager** dialog box (it should be located in the USB section).

3. Right click the entry and select **Update Driver**.



4. Select the Afinia H-Series 3D Driver folder (the default is **C:\Program Files\Afinia\Afinia 3D Printer\Drivers**).

5. A Free Motion Card entry should appear in the Device Manager list.

Updating the Printer ROM

Note: This is a function that should only be performed if necessary.

The H479 Printer ROM can only be updated using the Windows version of the Afinia Software. Follow these steps to perform the update:

1. With the H479 Printer on and initialized, select **Update ROM** from the **Tools** menu.
2. Click the **OK** button in the dialog asking you to confirm that you want to update the ROM.
3. Click **OK** in the next dialog to select the ROM update file.
4. Use the browse dialog to find the updated ROM file. This file will be located in the ***C:\Program Files\Afinia\System*** folder. The file name will include the ROM version just before the ***.ROM*** file extension.
5. Click the **Open** button when the correct file is selected.
6. Verify that you have selected the correct file and click **OK**. Click **OK** again to begin the update.
7. When notified that the update is complete, follow the prompts and power cycle the H479.
8. Initialize using the hardware button on the front of the Printer.
9. Select **About Afinia** under the **Help** menu and verify that the new ROM version has been applied.

Specifications

Printer Physical Characteristics

Printing Material	ABS or PLA Plastic
Layer Thickness	0.15 – 0.40 or 0.20－0.35 mm, depending on model, ROM version
Nozzle Diameter	0.40mm
Print Speed	10－100 cm^3/h
Print Size	140×140×135mm
Printer Weight	11 lb (5 KG)
Printer Size	245 × 260 × 350 mm

Specifications

Power Requirements	100-240 VAC, 50-60 Hz, 200W
Model Support	Auto-generated Support
Input Format	STL, UP3
Workstation compatibility	Win XP/Vista/Win7/Mac OSX

Environmental specifications

Ambient temperature	60°F～85°F
Relative humidity	20%～50%

Technical Support

For technical questions or support issues, contact Afinia Technical Support:

PH: 952-279-2643

support@afinia.com

www.afinia.com

Please have the Model and Serial Number of your Afinia H-Series 3D Printer available when contacting Technical Support.

Date of Purchase: ____________________

Place Purchased: ____

Serial Number: ____
(Located on back of Printer)

Notes

EXHIBIT F

AFINIA

Out-of-the-Box 3D Printing Experience
For Engineers, Educators and Hobbyists

Included
- The Afinia H-Series 3D Printer
- Easy-to-use 3D Software
- Handling tools
- Starter spool of 1.5 lbs of ABS plastic

Key Features
- Live tech support
- Ready to use out of the box
- Fully assembled
- High quality, inexpensive plastic filament

Get Started in 3 Easy Steps
- Install included software
- Calibrate printhead
- Ready to print within minutes!

Specifications

Small Footprint
- Under 11 lbs
- 245 x 260 x 350 mm
- Printing Envelope: 5″ cubed

Standalone Operation
- Choose your .stl file and printing parameter, then hit print. Printer may then be disconnected from the computer.

Output Quality
- Accuracy within .15 mm and has 30% of the strength of injection

Custom Software
- Compatible with Mac and PC
- Features an easy-to-use interface for laying out, orienting, duplicating, and scaling your designs.
- Design files can be created using a variety of online softwares, or by downloading from the extensive online community for free.
- Automatic calculation and placement of removable support material to ensure stable printing of arcs and overhangs.

Filaments
- Afinia offers both premium and value-line filament featuring consistent

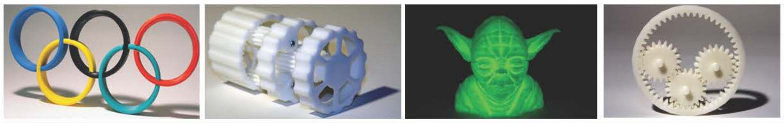


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EXHIBIT G

3D PRINTING INDUSTRY

INDUSTRY NEWS APPLICATIONS DESIGN
INDUSTRY INSIGHTS DIRECTORY
3D PRINTING INDUSTRY REPORT: MEDICAL AND HEALTHCARE

Executive Interview — Mitch Ackmann

BY 3D PRINTING INDUSTRY ON WED, AUGUST 28, 2013 · 3D PRINTERS, 3DP APPLICATIONS, EXECUTIVE INTERVIEW SERIES, INDUSTRY INSIGHTS, INTERVIEWS 2 COMMENTS

3D PRINTING INDUSTRY Executive Interview: Mitch Ackmann AFINIA

Mitch Ackmann is the President of up-and-coming US 3D printer company Afinia, and also holds the same position for Afinia's parent company Microboards based in Minnesota. With a background in electronics he has worked in this area (industry and location) for almost 30 years. Establishing the Microboard's Afinia subsidiary has seen him develop a company in the 3D printing industry that provides one of the most well-known desktop 3D printer brands in North America with a team of people that are extremely passionate about what they are doing and how they are doing it. They're also big fans of their users — or the Afiniacs!

3D Printing Industry: Can we start with a little history? Tell us about your background, your journey into 3D Printing with Afinia, the growth of the team and the H-Series.

Mitch Ackmann: It all started several years ago when our team at Microboards started looking at interesting technologies that had large up-side opportunity. We had done something similar in 1989 when we identified the potential in CD Recording and quickly began importing and selling the first CD Recording equipment and media in the US.

Having learned quite a bit about the technology, we then invented the first tower duplicator in the early 90's, and acquired a manufacturing plant in 2001 so that we could broaden our product line and launch a number of automated CD/DVD duplicating products.

Our experience and intellectual property in duplication automation became the basis of understanding how to improve the 3D printing process. Basically, a CD/DVD duplicator "applies" two-dimensional data to a rapidly-moving platform with very high precision. A 3D printer is a combination of components that, generally, does the same thing: firmware, software, servomotors and other electronics that duplicate 3D objects. Not a very big leap for us.

We started the 3D printing project with our existing Microboards teams. Marketing assessed the opportunity, players, products, software, customer support, warranty offerings and social media. Engineering brought in the most interesting printers, took them apart and identified one that fit our business plan.

Our engineers crafted a process to improve our selected printer and make it compliant with the demands of the US market. We tightened-up the supply chain and added resources to our customer support group.

One of the things that I have learned about bringing products to market is that the "product part", which is about 80%, is the easier side of the equation. I'm talking about design, alpha units, the firmware and software needed to make it work well. The really difficult part, the remaining 20%, is what separates a successful product from the others.

This 20% represents the less-glamorous things: a reliable supply chain, a consistent manufacturing process, packaging for shipping, inventory levels, spare parts, installation guides, documentation, warranties and customer support. This is the lower-tech, high-touch part of success that is often neglected.

For example, we have taken the base product of our H-series through some major improvements, namely in the electronics, firmware and software areas. Since July of 2012, we have improved the firmware and software three times for MAC and four times for PC. Many of the added features came to us from our customers – we enjoy the regular dialogue. Our

EXECUTIVE INTERVIEW SERIES

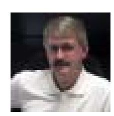
Executive Interview – David Reis

David Reis has taken the reins as the Chief Executive Officer for the newly formed 3D printing giant Stratasys Ltd following the finalisation…

Executive Interview — Espen Sivertsen

Last weekend, one of our video features was Type A Machines' CEO, Espen Sivertsen's presentation at TEDxLivermore. Here, in 3DPI's ongoing Executive Interview…

Executive Interview — Mitch Ackmann



Mitch Ackmann is the President of up-and-coming US 3D printer company Afinia, and also holds the same position for Afinia's parent company Microboards…

Executive Interview – Abe Reichental

At the 3D Printshow last month, 3DPI's

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'Afiniacs', are not shy about suggesting improvements – that's the beauty of working with people who are Makers at-heart.

3D Printing Industry: The H-Series 3D printer is based on licensed technology from Delta Micro Factory in China – Can you explain how Afinia came to take this route and how it is working for you?

Mitch Ackmann: Although we have a decent-sized technical staff, we chose to do what we had done successfully with CD recording equipment in the late 80's. We found someone with decent technology, established a good relationship with them, imported the product and readied it for mass-volume shipments. Simply put, it was the quickest way to get to market and see if 3D printing was right for Afinia and Microboards. How is this working? It's working great!

Although their technology had been previously available in the US, we found a number of ways that we could improve the product. We encouraged our partner to make a number of changes that not only improved performance but allowed for full FCC compliance, as well. Most importantly, we improved customer support by offering a number of options, including phone support. We've learned that customers appreciate talking to a real human being when they need help.

3D Printing Industry: In terms of markets and demographics, where are you finding the most uptake of the H-Series 3D printer?

Mitch Ackmann: Early on, we realized that there were three major markets: Education, Engineering and, those who we call, "Creatives". We have a group of Education Resellers who had been offering non-desktop 3D printing technology and design software. They have really taken to our H-Series 3D printer and enjoy the ease of setup and use. Plus, we have a generous warranty, personal support and a return policy. I don't think anyone else in the desktop 3D printing space offers those things to the degree that we do. We have also been chosen as the first 3D printer to be sold online by Best Buy, RadioShack, Staples-Canada, CDW, Tiger Direct and B&H Photo & Video.

3D Printing Industry: The H-Series 3D Printer seems to be a favorite in the maker community and has had some fantastic reviews from press and users a like — what is the stand out feature for you?

Mitch Ackmann: Thank you for asking that question. We have a saying around the office, "We will sell no product before its time." That's borrowed

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from a late 70's wine commercial, indicates a difference in our philosophy and, probably, why we came out of nowhere last year to be a pretty recognizable brand.

Our standout feature is the experience our customers have when they take the H-Series out of the box and begin to print. A few weeks ago, we had one reviewer say this: "I had it printing within 17 minutes from getting it out of the box, and I was taking photos at the same time." Now, this reviewer is one of the most experienced on the planet, but typically, our Afiniacs report that are printing within 30 minutes of unboxing.

We learned a couple of things from our CD/DVD duplicating customers: The installation guide must be bullet-proof, the product better darn well work perfectly out-of-the-box and someone has to answer the phone when a customer calls. We continue to be pleased by the positive reaction we get from reviewers. (Quite frankly, we assumed that all the products and companies in the space were like that. I guess there are some exceptions.)

So what makes us stand out as a company is our simple philosophy of a great product, at a great price with great service. And we don't just say it, we do it. Our warranty and return policy are the best in the industry. Those things keep people happy by giving them a better-than-expected experience, which leads to a strong reputation. I find it hard to believe that a leading 3D printing company can offer a couple of weeks or a couple of months for a warranty and get away with it.

3D Printing Industry: 3D Printing is still one of those technologies that has to be seen to be believed — particularly for the uninitiated — how do you connect with your target market(s)?

Mitch Ackmann: We do quite a few trade shows and have invested in a lot of video and social media content. It's funny, I still see people at shows that are completely transfixed when they see a 3D printer operate for the first time. I guess that's part of what makes this industry so much fun. We also appreciate the Maker Community. Those are the people who, in effect, drive the world's economy. They believe that everything can be improved and nothing is impossible. What a great bunch of people to associate with! We get a never-ending stream of product suggestions from them.

3D Printing Industry: What's next for Afinia?

Mitch Ackmann: We've been fortunate to have a high acceptance rate by Educators, Engineers and Creatives. They give us an increasing number of

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ideas for product improvements, and we are working hard to make those things a reality.

3D Printing Industry: Have you personally engaged with 3D printing — do you have your own 3D printer?

Mitch Ackmann: Microboards bought its first 3D printer in 2009 to make product prototypes. I think we paid more than $30,000. Now I understand why people visit our trade show booth and say things like: “I was across the aisle and looked at a $30,000 3D printer. How many of yours can I get for that price?” This is an actual quote from a School District Superintendant — she went on to buy twelve of our H-Series 3D printers and a bunch of filament.

3D Printing Industry: There is legitimate excitement and rapid uptake of 3D printing technologies, but there is also a great deal of hype, what is your personal opinion on this and how do you/Afinia combat inflated expectations as a result?

Mitch Ackmann You’re right, there is a lot of hype. To understand Afinia, one needs to understand Minnesotans. We don’t do hype, it only leads to disappointment. We probably are the least flashy people in the US. We do what we say, work as hard as we can and get the job done.

A reviewer once said something like, “The Afinia isn’t the world’s sexiest 3D printer – it just plain works.” That really sums up what we are all about. When you are straightforward about what your product does and you deliver, your customers are delighted and you get referrals. That’s pretty Minnesotan and is a good indication of how our Afiniacs are as people.

3D Printing Industry: What is the best reaction you have seen to someone seeing a 3D printer for the first time?

Mitch Ackmann: Early on, I was at a Maker Faire and a fellow gave me a USB drive with an STL file on it. He had been to five other 3D printer booths and none of them could successfully print his design. I loaded the file into our printer, and it ran perfectly – the guy was pretty shocked. It was a stand out moment for me — I was very pleased because it showed me that what we have is really special.

3D Printing Industry: In terms of 3D printing applications, do you have a favorite and will you share it with us?

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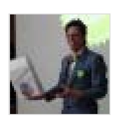

Michael Molitch-Hou Michael is the founder of The Reality™ Institute, a service institute

Mitch Ackmann:

As far as software applications, products from Sketchup, Autodesk, Solidworks and others cover the needs of the beginner to the expert. It is really great that these providers offer either free or discounted packages to educators. It gives our young people the opportunity to Make More and Consume Less.

As far as an application of 3D printing technology, we have a customer who is taking CT scan data and printing pre- and post-op models of vertebrae to help a client market a stem cell-based bone growth hormone. I'm always amazed at how our customers put our technology to work.

3D Printing Industry: What is your vision, including personal predictions, for the next 5 years for 3D printing in general; and for Afinia in particular?

Mitch Ackmann: Of course, I see a bright future for 3D printing and Afinia. It looks like we may become the only good-sized, independent 3D printer supplier, due to some acquisitions that may be in the works. I also see the industry becoming less about hype and more about reliable equipment and great customer support.

Here's our view of the market. There is some overlap between layers:

- Commercial 3D Printers: Used for complex manufacturing operations, sophisticated prototyping and advanced educational use, typically costing in the tens to hundreds of thousands of dollars. Well-established suppliers.
- ProSumer Printers: Used for basic commercial prototyping, very small-scale manufacturing, general educational use and upper-end maker/hobbyist applications. These 3D printer suppliers have mature supply chains, and customer support infrastructures.
- Kits & Other: Used for some ProSumer applications. These are newer market entrants that are in the process of establishing their infrastructures. They may also rely upon forums and/or discussion groups to support their customers.

We are firmly situated in the ProSumer market segment. This is illustrated by the major corporations and educational institutions that have invested in multiple pieces of our equipment.

We see a shakeout occurring in the ProSumer segment as the hype and great expectations are tempered by larger numbers of consumer's posting

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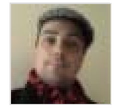
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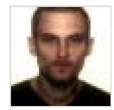
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their after-sale experience on social media. This is happening now.

As far as future products, there are a number of patents that will expire in the next few years, which will open up even more opportunity in the 3D printing space. It will be interesting to see what people come up with.

We will also see increased competition from 3D printers manufactured in the Far East. These companies tend to develop products and attempt to drive them into the US market on price alone – and in most cases you get what you pay for. Desktop 3D printers are designed to simplify the prototyping process. Since every application is unique, you need a versatile product offering and skilled staff to put the right solution to work in each situation. We pride ourselves on having great pre-sale and post-sale support for exactly that reason.

There is also some risk to our industry from the growing number of crowd funded 3D printer start-ups. Some of them have done their homework, assembled a team, solidified their supply chain and staffed-up to provide a great customer experience. Some haven't. Things will shakeout pretty quickly. I just hope that it doesn't hurt our industry too much, in the process.

Speaking of start-ups, Afinia was effectively a start-up last year. We've done pretty well since then due to our ability to piggyback on what we've learned in the last 20 years from Microboards.

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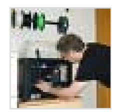

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