REMOVABLE SUPPORT FOR FREE FORM OBJECTS

Background of the Invention

1. Field of the Invention

The present invention relates generally to additive fabrication techniques. More particularly, the present invention relates to a method and apparatus to support objects with downward facing surfaces during additive fabrication.

2. Description of the Related Art

Traditionally, the manufacture of articles or objects is accomplished through subtractive processes, such as molding, casting, machining, or etching. Examples of the objects formed by subtractive fabrication include extremely dissimilar products such as semiconductor devices, jet airplane wings, and furniture.

One of the problems with subtractive fabrication is that it requires very expensive tooling and complex machining processes. Furthermore, by definition, subtractive fabrication requires a larger volume of object material than what the object actually requires. Therefore, the excess material (which is sometimes of greater volume than the object itself) that is machined or etched away becomes waste and is typically discarded.

In contrast to subtractive fabrication, solid free-form fabrication (SFF) refers to a group of manufacturing technologies that use additive techniques. Through layered manufacturing, physical objects may be created automatically through computer modeling. The advantage of SFF is that the objects may be produced from the models, not only without complex machinery, but also without the limits of the machinery.

By adding material to instead of subtracting from the object, SFF provides for the construction of parts with shapes and geometries that are unattainable through subtractive processes. In addition, SFF minimizes the waste of object material and reduces cost by eliminating the need for expensive machining tools compared to subtractive processes. Exemplary forms of SFF include fused-deposition modeling (FDM), stereo-lithography (SLA), and selective laser sintering (SLS).

While these various forms of SFF are advantageous over traditional subtractive fabrication, additive fabrication is still a technology that requires great care to utilize. The manufacturing of a free form object remains a delicate process because the object is typically built layer by layer. While build time is usually quicker than that of subtractive fabrication, SFF processes must overcome a multitude of technical problems. Common problems include as poor surface finish, inadequate bonding between layers, and a limited choice of build materials.

Perhaps the most challenging problem associated with additive fabrication is providing support for objects with downward facing surfaces. During fabrication, each layer of a free form object must be supported. In objects without downward facing surfaces, the layers are supported either by a standard flat target platform or by adjacent layers of the object, which are supported by the platform. Because downward facing regions cannot be supported in either fashion, such regions in a free form object would simply succumb to gravity and fail to achieve the desired form and shape.

Several methods for supporting downward facing regions have been devised. In U.S. Pat. No. 4,863,538 to Deckard and U.S. Pat. No. 5,340,656 to Sachs et al., an unbonded powder support layer is formed to support a SLS process, in which powders are sintered with laser scans. Unfortunately, Deckard and Sachs are limited to powder based processes and are not suitable for other forms of SFF, particularly applications using flowable modeling materials.

U.S. Pat. No 6,080,343 to Kaufman et al. teaches rotating the object while the build material is being deposited. However, rotation can provide support only for downward facing regions, for which support can be gleaned from the object itself. In addition, the rotational system in Kaufman is very expensive, requiring both sophisticated equipment and highly trained operators.

Other methods for supporting downward facing regions focus on providing structural support to the regions. U.S. Pat. No. 5,141,680 to Almquist discloses structural supports comprising similar materials to the object. Almquist provides for a method to provide support using columns and webs. Unfortunately, the finish of the downward facing surfaces of the object is poor after the supports have been removed. As a

consequence of the poor surface quality for downward facing surfaces, the object must be oriented with its important features facing upward.

In contrast, U.S. Pat. No. 5,617,911 to Sterett et al. uses a dissimilar material to produce the support structures. The key to this process is to select the dissimilar material that forms a weak bond joint with the object. Unfortunately, the use of forcible separation in both Almquist and Sterett may potentially damage the object, particularly if the features are small and the build material is brittle.

U.S. Pat. No. 6,572,807 to Fong teaches the forming of a cold weld joint between a free form object and its support. The joint is formed from a single phase change material having an outer surface temperature below its flowable temperature and used to create a separation zone between the free form object and its support. Because the joint comprises droplets that lack sufficient energy to bond with the object, the object may be severed from the support along the joint.

One of the major problems in the Fong process is that the object building cycle is increased substantially because of the numerous temperature requirements to form the support, cold weld joint, and the object. Furthermore, the distance required between the dispenser and the target to cool the droplets may result in reduced targeting accuracy. In addition, the support may be difficult to separate from entrapped downward facing regions regardless of the joint because it is a solid mass.

In view of the foregoing, it is desirable to have a method and apparatus for providing an easy to remove support for downward facing regions of a free form object. It is further desirable to have a removable support that may be separated from the free form object with minimal force and strain on the object. It is further desirable to have a removable support that is able to support downward facing regions featuring radical or complicated geometries.

Brief Description of the Drawings

The present invention will be readily understood by the following detailed description in conjunction with the accompanying drawings. To facilitate this description, like reference numerals designate like structural elements.

Figure 1 illustrates a droplet deposition modeling (DDM) system in accordance with one embodiment of the present invention.

Figure 2 illustrates a free form object that may be fabricated by the DDM system in accordance with one embodiment of the present invention.

Figure 3 illustrates a partially built free form object in the process of being fabricated by the DDM system.

Figure 4 illustrates completed free form object, in which the downward facing surfaces and regions are supported by removable supports in accordance with one embodiment of the present invention.

Figure 5 is a more detailed illustration of an interface between the downward facing surface and the removable support.

Figure 6 is a chart illustrating the relationship between the melting range and the molecular weight of a rapid phase change liquid polymer in accordance with one embodiment of the present invention.

Figure 7 illustrates the free form object during separation from the removable supports in accordance with one embodiment of the present invention.

Figure 8 is a flow chart of a method for forming a downward facing surface of an object by additive fabrication in accordance with one embodiment of the present invention.

Detailed Description

A method and apparatus for providing a removable support for objects formed by additive fabrication are provided. In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be understood, however, to one skilled in the art, that the present invention may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure the present invention.

Figure 1 illustrates a droplet deposition modeling (DDM) system 10 in accordance with one embodiment of the present invention. DDM system 10 includes an actuator 12 coupled to a pair of dispensers 14 and 16, each of which is disposed over a platform 18. In this particular embodiment, support dispenser 14 is used to provide a supply of support material to deposit onto a target, such as platform 18. Object dispenser 16 is also to provide a supply of object material to deposit onto platform 18. Inkjet printing equipment has been found to be suitable for both types of dispenser.

Actuator 12 is coupled to an external processor 20, which provides linear guiding for dispensers 14 and 16. The purpose of DDM system 10 is to fabricate an object having downward facing surfaces by producing a removable support using additive techniques. The removable support is to support the downward facing surfaces of the object during fabrication, against the destructive forces of gravity. After the object is formed, the removable support may be separated without damaging the object.

Figure 2 illustrates a free form object 22 that may be fabricated by DDM system 10 in accordance with one embodiment of the present invention. In this exemplary case, free form object 22 includes a sloped downward facing surface 24 and an entrapped downward facing surface 26. Free form object 22 also includes a pair of pillars 32. As is clear from the drawing, surfaces 24 and 26 require support during layer by layer additive fabrication. Without support sloped downward facing region 28 and entrapped downward facing region 30 would collapse from the effects of gravity.

Figure 3 illustrates a partially built free form object 22' in the process of being fabricated by DDM system 10. Through computer aided designs and models provided through external processor 20, actuator 12 is programmed to provide linear guidance to dispensers 14 and 16. To support surfaces 24 and 26 and regions 28 and 30, support dispenser 14 begins depositing a number of discrete droplets 34 of support material to form a sloped removable support 36 and an entrapped removable support 38. To maintain optimal accuracy for droplet deposition, the distance between dispensers 14 and 16 and the target preferably ranges from about 1 mm to about 3 mm.

A key characteristic of the present invention is that the support material is not fused into a solid filled mass. Instead, the support material for removable supports 36 and 38 includes a rapid phase change liquid to enable droplets 34 to remain discrete and separable after deposition. More specifically, the composition of the droplets is chosen so that the phase change of droplets 34 begins in flight after dispensing and before reaching the target. At the same time, object dispenser 16 may be programmed to deposit object material to form free form object 22.

Figure 4 illustrates completed free form object 22, in which downward facing surfaces 24 and 26 and regions 28 and 30 are supported by removable supports 36 and 38 in accordance with one embodiment of the present invention. In particular, entrapped downward facing region 30 and pillars 32 are an example of a complicated geometric structure that is very difficult to form by most SFF techniques. For example, pillars 32 cannot be deposited by simply rotating free form object 22 because there is no orientation that would provide support from either adjacent layers of object 22 or platform 18. Furthermore, while a solid filled mass may be used to support region 30 and pillars 32, such a mass would be extremely difficult to separate and remove from free form object 22 after fabrication.

Figure 5 is a more detailed illustration of an interface between downward facing surface 26 and removable support 38. To produce the structure of discrete particles in removable support 38, the support material includes a rapid phase change liquid. Before deposition, the support material is maintained at a temperature that allows the formation of

liquid droplets 34, for example, from about 120°C to about 135°C for polyethylene. After ejection from support dispenser 14, the droplets 34 begin to cool and solidify.

During flight, an outer surface 40 of droplets 34 experiences a faster temperature reduction relative to the interior 42, therefore outer surface 40 solidifies more quickly than interior 42. The speed of the solidification of outer surface 40 may be controlled within a narrow operating range. Solidification should be slow enough to allow each of droplets 34 to form a bond with adjacent droplets 34. However, solidification should also be quick enough to support an additional layer of droplet or object material.

Figure 6 is a chart illustrating the relationship between the melting range and the molecular weight of a rapid phase change liquid polymer in accordance with one embodiment of the present invention. More specifically, the chart tracks the behavior of polyethylene, which is a crystalline polymer having a narrow melting range. Because the flight time of each droplet of rapid phase change liquid is so short, the droplet must begin solidifying in response to a very small temperature drop. Both the melting point and the change rate of polyethylene increases when its molecular weight is increased.

As depicted in Figure 6, if a polymer has a molecular weight distribution between lines 44 and 46, it will have a melting range between lines 48 and 50. However, at an overly high molecular weight, the polymer will become overly viscous for droplet formation. To ensure that polyethylene is able to solidify within a very small temperature drop, it should have a narrow molecular weight distribution. In one embodiment of the present invention, polyethylene with an average molecular weight of about 1,000 with a narrow distribution may be used.

Referring back to Figure 5, the object material of downward facing region 30 must possess certain characteristics to avoid mixing with droplets 34 of removable support 38. The object material must resist gravity, inertia of the object material when it is deposited, and any wetting effect with droplets 34. In one embodiment of the present invention, object material with high surface tension, high viscosity, and poor surface wettability is chosen to maintain the separation.

Figure 7 illustrates free form object 22 during separation from removable supports 36 and 38 in accordance with one embodiment of the present invention. Because droplets 34 that comprise removable supports 36 and 38 are discrete, a light mechanical force has been found sufficient to separate and dislodge removable support 36 and 38 from free form object 22. In one embodiment, physical shaking and brushing of the object was used to crumble and separate the removable supports from the free form object. The used support material may then be collected and recycled.

Figure 8 is a flow chart of a method 50 for forming a downward facing surface of an object by additive fabrication in accordance with one embodiment of the present invention. Method 50 begins at an act 52, which provides a supply of support material, such as polyethylene with an average molecular weight of about 1,000. The polyethylene should be maintained at a temperature of about 120°C to about 135°C. The support material is used to form droplets, which are about 40 microns to about 80 microns in diameter when dispensed from an inkjet. The droplets are dispensed towards a target in an act 54 to form a removable support for the object.

A supply of object material is provided in an act 56. In one embodiment, the object material may be paraffin wax, which is maintained at a temperature of about 70°C to about 80°C to maintain a low viscosity. The object material is then deposited onto the removable support to form a downward facing surface in an act 58. After the object is formed, the removable support may be removed in an act 60 using a light mechanical force, such as shaking, vibrating or brushing.

Other embodiments of the invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention. Furthermore, certain terminology has been used for the purposes of descriptive clarity, and not to limit the present invention. The embodiments and preferred features described above should be considered exemplary, with the invention being defined by the appended claims.

CLAIMS

1. A method for forming a downward facing surface of an object by additive fabrication, comprising:

providing a supply of support material, wherein said support material is to form a plurality of droplets;

dispensing said plurality of droplets towards a target, wherein said plurality of droplets is to form a removable support and wherein each of said plurality of droplets in said removable support remains discrete;

providing a supply of object material;

depositing said object material onto said removable support to form said downward facing surface; and

removing said removable support.

2. The method as recited in claim 1, wherein a surface of each of the plurality of droplets begins to solidify after the dispensing the plurality of droplets.

3. The method as recited in claim 2, wherein the plurality of droplets is dispensed about 1 mm to about 3 mm from the target.

4. The method as recited in claim 1, wherein the support material comprises a rapid phase change liquid.

5. The method as recited in claim 4, wherein the rapid phase change liquid is a crystalline polymer.

6. The method as recited in claim 5, wherein the crystalline polymer is polyethylene having an average molecular weight of about 1,000.

7. The method as recited in claim 6, further comprising maintaining the support material at a temperature of about 120°C to about 135°C.

8. An droplet deposition modeling system for forming a downward facing surface of an object by additive fabrication, comprising:

a first dispenser for providing a supply of support material, wherein said support material is to form a plurality of droplets;

a second dispenser for providing a supply of object material, wherein said object material is to form said downward facing surface of said object;

an actuator coupled to said first and second dispensers, wherein said actuator is to position said first and second dispensers; and

a target for receiving said droplets and said object material from said first and second dispensers, wherein said droplets are to form a removable support to support said downward facing surface of said object and wherein each of said droplets in said removable support remain discrete.

9. The droplet deposition modeling system as recited in claim 8, wherein a surface of each of the plurality of droplets begins to solidify after the dispensing the plurality of droplets.

10. The droplet deposition modeling system as recited in claim 9, wherein the plurality of droplets is dispensed about 1 mm to about 3 mm from the target.

11. The droplet deposition modeling system as recited in claim 8, wherein the support material comprises a rapid phase change liquid.

12. The droplet deposition modeling system as recited in claim 11, wherein the rapid phase change liquid is a crystalline polymer.

13. The droplet deposition modeling system as recited in claim 12, wherein the crystalline polymer is polyethylene having an average molecular weight of about 1,000.

14. The droplet deposition modeling system as recited in claim 13, further comprising maintaining the support material at a temperature of about 120°C to about 135°C.

15. A removable support for a downward facing surface of an object formed by additive fabrication, comprising a first set of droplets, wherein said each of first set of droplets is to form a first set of bonds to and support said downward facing surface and wherein said each of said first set of droplets remains discrete.

16. The removable support recited in claim 15, further comprising a second set of droplets of support material, wherein each of said second set of droplets is to form a second set of bonds to the first set of droplets and wherein each of said second set of droplets remains discrete.

17. The removable support recited in claim 16, wherein the support material includes a rapid phase change liquid.

18. The removable support as recited in claim 17, wherein the rapid phase change liquid is a crystalline polymer.

19. The removable support as recited in claim 18, wherein the crystalline polymer is polyethylene having an average molecular weight of about 1,000.

20. The removable support as recited in claim 19, wherein each of said first set of droplets and each of the second set of droplets have a diameter of about 40 microns to about 80 microns.