

Chapter 6

Extrusion-Based Systems

6.1 Introduction

This chapter deals with AM technologies that use extrusion to form parts. These technologies can be visualized as similar to cake icing, in that material contained in a reservoir is forced out through a nozzle when pressure is applied. If the pressure remains constant, then the resulting extruded material (commonly referred to as “roads”) will flow at a constant rate and will remain a constant cross-sectional diameter. This diameter will remain constant if the travel of the nozzle across a depositing surface is also kept at a constant speed that corresponds to the flow rate. The material that is being extruded must be in a semi-solid state when it comes out of the nozzle. This material must fully solidify while remaining in that shape. Furthermore, the material must bond to material that has already been extruded so that a solid structure can result.

Since material is extruded, the AM machine must be capable of scanning in a horizontal plane as well as starting and stopping the flow of material while scanning. Once a layer is completed, the machine must index upwards, or move the part downwards, so that a further layer can be produced.

There are two primary approaches when using an extrusion process. The most commonly used approach is to use temperature as a way of controlling the material state. Molten material is liquefied inside a reservoir so that it can flow out through the nozzle and bond with adjacent material before solidifying. This approach is similar to conventional polymer extrusion processes, except the extruder is vertically mounted on a plotting system rather than remaining in a fixed horizontal position.

An alternative approach is to use a chemical change to cause solidification. In such cases, a curing agent, residual solvent, reaction with air, or simply drying of a “wet” material permits bonding to occur. Parts may therefore cure or dry out to become fully stable. This approach may be more applicable to biochemical applications where materials must have biocompatibility with living cells and so choice of material is very restricted. However, industrial applications may also exist,

perhaps using reaction injection molding-related processes rather than relying entirely on thermal effects.

This chapter will start off by describing the basic principles of extrusion-based additive manufacturing. Following this will be a description of the most widely used extrusion-based technology, developed and commercialized by Stratasys, USA. Bioplotting equipment for tissue engineering and scaffold applications commonly use extrusion technology and a discussion on how this differs from the Stratasys approach will ensue. Finally, there have been a number of interesting research projects employing, adapting, and developing this technology, and this will be covered at the end of the chapter.

6.2 Basic Principles

There are a number of key features that are common to any extrusion-based system:

- Loading of material
- Liquification of the material
- Application of pressure to move the material through the nozzle
- Extrusion
- Plotting according to a predefined path and in a controlled manner
- Bonding of the material to itself or secondary build materials to form a coherent solid structure
- Inclusion of support structures to enable complex geometrical features

These will be considered in separate sections to fully understand the intricacies of extrusion-based AM.

A mathematical or physics-based understanding of extrusion processes can quickly become complex, since it can involve many nonlinear terms. The basic science involves extrusion of highly viscous materials through a nozzle. It is reasonable to assume that the material flows as a Newtonian fluid in most cases [1]. Most of the discussion in these sections will assume the extrusion is of molten material and may therefore include temperature terms. For solidification, these temperature terms are generally expressed relative to time; and so temperature could be replaced by other time-dependent factors to describe curing or drying processes.

6.2.1 *Material Loading*

Since extrusion is used, there must be a chamber from which the material is extruded. This could be preloaded with material, but it would be more useful if there was a continuous supply of material into this chamber. If the material is in a liquid form, then the ideal approach is to pump this material. Most bulk material is,

however, supplied as a solid and the most suitable methods of supply are in pellet or powder form, or where the material is fed in as a continuous filament. The chamber itself is therefore the main location for the liquification process. Pellets, granules, or powders are fed through the chamber under gravity or with the aid of a screw. Materials that are fed through the system under gravity require a plunger or compressed gas to force it through the narrow nozzle. Screw feeding not only pushes the material through to the base of the reservoir but can be sufficient to generate the pressure needed to push it through the nozzle as well. A continuous filament can be pushed into the reservoir chamber, thus providing a mechanism for generating an input pressure for the nozzle.

6.2.2 *Liquification*

The extrusion method works on the principle that what is held in the chamber will become a liquid that can eventually be pushed through the die or nozzle. As mentioned earlier, this material could be in the form of a solution that will quickly solidify following the extrusion, but more likely this material will be liquid because of heat applied to the chamber. Such heat would normally be applied by heater coils wrapped around the chamber and ideally this heat should be applied to maintain a constant temperature in the melt (see Fig. 6.1). The larger the chamber, the more difficult this can become for numerous reasons related to heat transfer, thermal currents within the melt, change in physical state of the molten material, location of temperature sensors, etc.

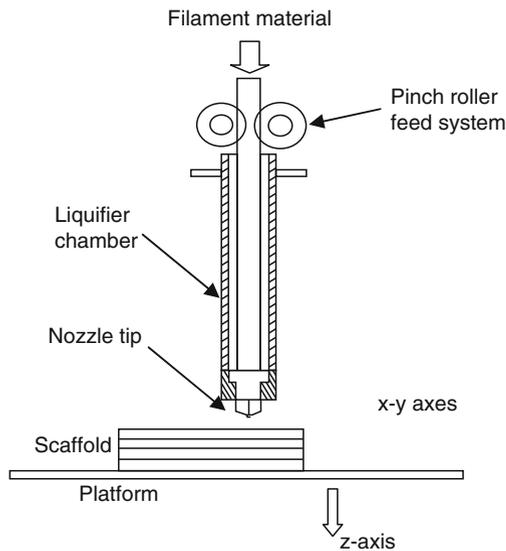


Fig. 6.1 Schematic of extrusion-based systems

The material inside the chamber should be kept in a molten state but care should be taken to maintain it at as low a temperature as possible since some polymers degrade quickly at higher temperatures and could also burn, leaving residue on the inside of the chamber that would be difficult to remove and that would contaminate further melt. A higher temperature inside the chamber also requires additional cooling following extrusion.

6.2.3 Extrusion

The extrusion nozzle determines the shape and size of the extruded filament. A larger nozzle diameter will enable material to flow more rapidly but would result in a part with lower precision compared with the original CAD drawing. The diameter of the nozzle also determines the minimum feature size that can be created. No feature can be smaller than this diameter and in practice features should normally be large relative to the nozzle diameter to faithfully reproduce them with satisfactory strength. Extrusion-based processes are therefore more suitable for larger parts that have features and wall thicknesses that are at least twice the nominal diameter of the extrusion nozzle used. Material will flow through the nozzle is controlled by the pressure drop between the chamber and the surrounding atmosphere.

The extrusion process used for AM may not be the same as conventional extrusion. For example, the pressure developed to push the molten material through the nozzle is typically not generated by a screw mechanism. However, to understand the process it may be useful to study a traditional screw-fed extrusion process as described, for example, by Stevens and Covas [2]. Mass flow through a nozzle is related to pressure drop, nozzle geometry, and material viscosity. The viscosity is of course primarily a function of temperature. Since no special dies or material mixing is required for this type of application, it can be said to behave in a similar manner to a single Archimedean screw extruder as shown in Fig. 6.2.

Using simple screw geometry, molten material will gradually move along the screw channel toward the end of the screw where the nozzle is. The velocity W of material flow along the channel will be

$$W = \pi D N \cos \phi \quad (6.1)$$

where D is the screw diameter, N is the screw speed, and ϕ is the screw angle. The velocity of the material U toward the nozzle is therefore

$$U = \pi D N \sin \phi \quad (6.2)$$

For a constant helix angle, the volumetric flow caused by the screw in the barrel, known as drag flow Q_D , is proportional to the screw dimensions and speed

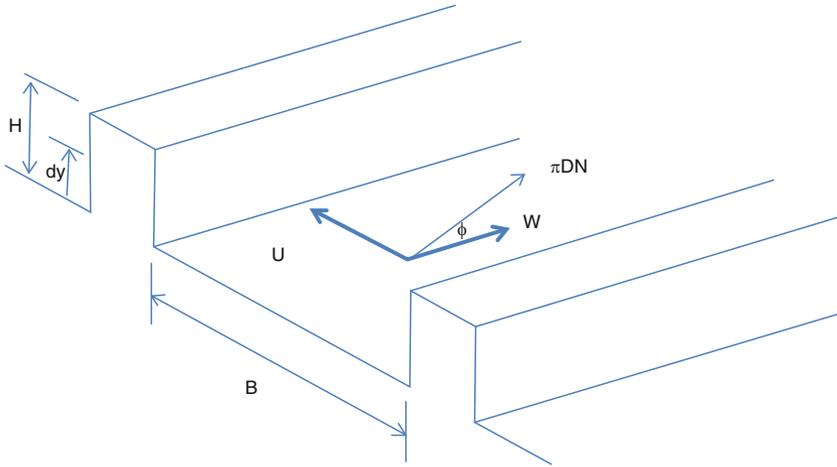


Fig. 6.2 A single Archimedian screw segment. Material flows along the channel in direction W and along a fixed barrel in direction U

$$Q_D \propto D^2 N h$$

Since we are operating under drag flow, the relative velocity of the molten material will be W for the material that is in contact with the screw, and 0 for the material in contact with the stationary walls of the barrel. We must therefore integrate over the height of the screw. Generalizing the molten material traveling down this rectangular channel, the along-channel flow Q_D through a channel of B width and dy height can be expressed as

$$\begin{aligned}
 Q_D &= \int_0^H WB \, dy \\
 &= \frac{WBH}{2}
 \end{aligned}
 \tag{6.3}$$

where H is the screw depth. $W/2$ is defined as the mean down-channel velocity. Substituting for W (6.1) for the screw feed system gives

$$Q_D = \frac{\pi}{2} DNBH \cos \phi$$

We must now consider pressure flow in the channel. Flow through a slit channel, width L , height H , and of infinite length can be derived from the following fundamental equation for shear stress τ

$$\tau(x) = \frac{\Delta P}{L} \cdot x \quad (6.4)$$

where x is perpendicular to the flow direction and ΔP is the pressure change along the channel. For Newtonian flow τ can also be expressed as

$$\tau = -\eta \cdot \frac{dv_z}{dx} \quad (6.5)$$

where η is the dynamic viscosity of the molten polymer, defined as a Newtonian fluid. Combining these (6.4) and (6.5), we obtain

$$-\eta \frac{dv_z}{dx} = \frac{\Delta P}{L} dx \quad (6.6)$$

Integration of (6.6) over x , with boundary conditions for $v_z = 0$ when $x = \pm H/2$ (i.e., around the center of the channel and assuming a no-slip boundary) will give the mean velocity for flow of a fluid through a rectangular slit of an infinite length.

$$\begin{aligned} v_z(x) &= \frac{\Delta P}{2\eta L} \left[\frac{H}{2} - x^2 \right] \\ \text{mean velocity } v &= \frac{1}{H} \int_{-\frac{H}{2}}^{\frac{H}{2}} v_z(x) \\ &= \frac{\Delta P H^2}{12\eta L} \end{aligned} \quad (6.7)$$

This velocity can be considered as a result of the back pressure created by the inability for all the molten material to be pushed through an extrusion die (or nozzle) at the end of the channel, which flows opposite the drag flow of the screw. Since the pressure flow rate is volume over time, factoring in B as the screw pitch, or the breadth of the channel and H as the screw depth or the height of the channel:

$$Q_P = \frac{BH^3}{12\eta} \cdot \frac{dP}{dz} \quad (6.8)$$

The pressure calculation for a screw feed is similar to that of flow down a rectangular slit or channel. In order for material to flow down the screw, and therefore material to extrude from the output nozzle, the pressure flow Q_P must exceed the drag flow to give a total flow

$$\begin{aligned}
 Q_T &= Q_P - Q_D \\
 &= \frac{BH^3}{12\eta} \cdot \frac{dP}{dz} - \frac{WBH}{2}
 \end{aligned} \tag{6.9}$$

This provides us with an expression that describes the flow of material back up the rectangular channel as well as down the screw feed, therefore modeling the drag flow generated by the screw and the back flow generated by the pressure differential of the chamber and the output nozzle. A similar pressure flow expression can be formulated for a circular nozzle to model the extrusion process itself. It is assumed that only melt flow exists and that there is a stable and constant temperature within the melt chamber. Both of these are reasonable assumptions. However, for an AM-based extrusion system a gravity term should be included.

6.2.4 Solidification

Once the material is extruded, it should ideally remain the same shape and size. Gravity and surface tension, however, may cause the material to change shape, while size may vary according to cooling and drying effects. If the material is extruded in the form of a gel, the material may shrink upon drying, as well as possibly becoming porous. If the material is extruded in a molten state, it may also shrink when cooling. The cooling is also very likely to be nonlinear. If this nonlinear effect is significant, then it is possible the resulting part will distort upon cooling. This can be minimized by ensuring the temperature differential between the chamber and the surrounding atmosphere is kept to a minimum (i.e., use of a controlled environmental chamber when building the part) and also by ensuring the cooling process is controlled with a gradual and slow profile.

It is reasonable to assume that an extrusion-based AM system will extrude from a large chamber to a small nozzle through the use of a conical interface. As mentioned before, the melt is generally expected to adhere to the walls of the liquefier and nozzle with zero velocity at these boundaries, subjecting the material to shear deformation during flow. The shear rate $\dot{\gamma}$ can be defined as [1]

$$\dot{\gamma} = -\frac{dv}{dr} \tag{6.10}$$

and the shear stress as

$$\tau = \left(\frac{\dot{\gamma}}{\phi} \right)^{\frac{1}{m}} \tag{6.11}$$

where m represents the flow exponent and ϕ represents the fluidity. The general flow characteristic of a material and its deviation from Newtonian behavior is reflected in the flow exponent m .

6.2.5 Positional Control

Like many AM technologies, extrusion-based systems use a platform that indexes in the vertical direction to allow formation of individual layers. The extrusion head is typically carried on a plotting system that allows movement in the horizontal plane. This plotting must be coordinated with the extrusion rate to ensure smooth and consistent deposition.

Since the plotting head represents a mass and therefore contains an inertial element when moving in a specific direction, any change in direction must result in a deceleration followed by acceleration. The corresponding material flow rate must match this change in speed or else too much or too little material will be deposited in a particular region. For example, if the extrusion head is moving at a velocity v parallel to a nominal x direction and is then required to describe a right angle so that it then moves at the same velocity v in the perpendicular y direction. At some point the instantaneous velocity will reach zero. If the extrusion rate is not zero at this point, then excess material will be deposited at the corner of this right angled feature.

Since the requirement is to move a mechanical extrusion head in the horizontal plane then the most appropriate mechanism to use would be a standard planar plotting system. This would involve two orthogonally mounted linear drive mechanisms like belt drives or lead-screws. Such drives need to be powerful enough to move the extrusion chamber at the required velocity and be responsive enough to permit rapid changes in direction without backlash effects. The system must also be sufficiently reliable to permit constant movement over many hours without any loss in calibration. While cheaper systems often make use of belts driven by stepper motors, higher cost systems typically use servo drives with lead-screw technology.

Since rapid changes in direction can make it difficult to control material flow, a common strategy would be to draw the outline of the part to be built using a slower plotting speed to ensure that material flow is maintained at a constant rate. The internal fill pattern can be built more rapidly since the outline represents the external features of the part that corresponds to geometric precision. This outer shell also represents a constraining region that will prevent the filler material from affecting the overall precision. A typical fill pattern can be seen in Fig. 6.3. Determination of the outline and fill patterns will be covered in a later section of this chapter.

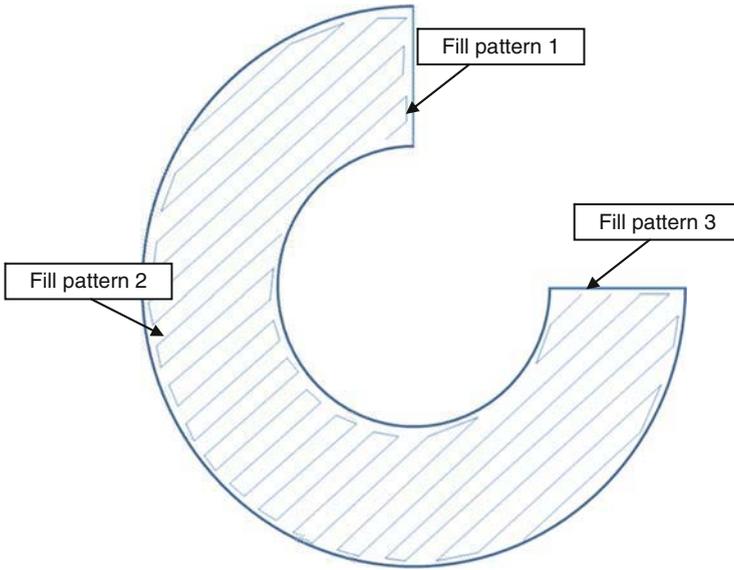


Fig. 6.3 A typical fill pattern using an extrusion-based system, created in three stages (adapted from [5])

6.2.6 Bonding

For heat-based systems there must be sufficient residual heat energy to activate the surfaces of the adjacent regions, causing bonding. Alternatively, gel-based systems must contain residual solvent or wetting agent in the extruded filament to ensure the new material will bond to the adjacent regions that have already been deposited. In both cases, we visualize the process in terms of energy supplied to the material by the extrusion head.

If there is insufficient energy, the regions may adhere, but there would be a distinct boundary between new and previously deposited material. This can represent a fracture surface where the materials can be easily separated. Too much energy may cause the previously deposited material to flow, which in turn may result in a poorly defined part.

Once the material has been extruded, it must solidify and bond with adjacent material. Yardimci defined a set of governing equations that describe the thermal processes at work in a simple extruded road, laid down in a continuous, open-ended fashion along a direction x , based on various material properties [3].

$$\rho \frac{\partial q}{\partial t} = k \frac{\partial^2 T}{\partial x^2} - S_c - S_l \quad (6.12)$$

where ρ is the material density, q is the specific enthalpy, and k the effective thermal conductivity. T is the cross-sectional average road temperature. The term S_c is a sink term that describes convective losses.

$$S_c = \frac{h}{h_{\text{eff}}}(T - T_{\infty}) \quad (6.13)$$

h is the convective cooling heat transfer coefficient and h_{eff} is a geometric term representing the ratio of the road element volume to surface for convective cooling. This would be somewhat dependent on the diameter of the nozzle. The temperature T_{∞} is the steady-state value of the environment. The term S_1 is a sink/source term that describes the thermal interaction between roads.

$$S_1 = \frac{k}{\text{width}^2}(T - T_{\text{neigh}}) \quad (6.14)$$

Where “width” is the width of the road and T_{neigh} is the temperature of the relevant neighboring road. If material is laid adjacent to more material, this sink term will slow down the cooling rate. There is a critical temperature T_c above which a diffusive bonding process is activated and below which bonding is prohibited. On the basis of this, we can state a bonding potential φ as

$$\varphi = \int_0^{\tau} (T - T_c) d\tau \quad (6.15)$$

6.2.7 Support Generation

All AM systems must have a means for supporting free-standing and disconnected features and for keeping all features of a part in place during the fabrication process. With extrusion-based systems such features must be kept in place by the additional fabrication of supports. Supports in such systems take two general forms:

- Similar material supports
- Secondary material supports

If an extrusion-based system is built in the simplest possible way then it will have only one extrusion chamber. If it has only one chamber then supports must be made using the same material as the part. This may require parts and supports to be carefully designed and placed with respect to each other so that they can be separated at a later time. As mentioned earlier, adjustment of the temperature of the part material relative to the adjacent material can result in a fracture surface effect. This fracture surface can be used as a means of separating the supports from the part material. One possible way to achieve this may be to change the layer separation



Fig. 6.4 A medical model made using extrusion-based AM technology from two different color materials, highlighting a bone tumor (courtesy of Stratasys)

distance when depositing the part material on top of the support material or vice versa. The additional distance can affect the energy transfer sufficiently to result in this fracture phenomenon. Alternatively, adjustment of the chamber or extrusion temperature when extruding supports might be an effective strategy. In all cases however, the support material will be somewhat difficult to separate from the part.

The most effective way to remove supports from the part is to fabricate them in a different material. The variation in material properties can be exploited so that supports are easily distinguishable from part material, either visually (e.g., using a different color material), mechanically (e.g., using a weaker material for the supports), or chemically (e.g., using a material that can be removed using a solvent without affecting the part material). To do this, the extrusion-based equipment should have a second extruder. In this way, the secondary material can be prepared with the correct build parameters and extruded in parallel with the current layer of build material, without delay. It may be interesting to note that a visually different material, when not used for supports, may also be used to highlight different features within a model, like the bone tumor shown in the medical model of Fig. 6.4.

6.3 Plotting and Path Control

As with nearly all additive manufacturing systems, extrusion-based machines mostly take input from CAD systems using the generic STL file format. This file format enables easy extraction of the slice profile, giving the outline of each

slice. As with most systems, the control software must also determine how to fill the material within the outline. This is particularly crucial to this type of system, however, since extrusion heads physically deposit material that fills previously vacant space. There must be clear access for the extrusion head to deposit fill material within the outline without compromising the material that has already been laid down. Additionally, if the material is not laid down close enough to adjacent material, it will not bond effectively. In contrast, laser-based systems can permit, and in fact generally require, a significant amount of overlap from one scan to the next and thus there are no head collision or overfilling-equivalent phenomena.

As mentioned earlier, part accuracy is maintained by plotting the outline material first, which will then act as a constraining region for the fill material. The outline would generally be plotted with a lower speed to ensure consistent material flow. The outline is determined by extracting intersections between a plane (representing the current cross section of the build) and the triangles in the STL file. These intersections are then ordered so that they form a complete, continuous curve for each outline (there may be any number of these curves, either separate or nested inside of each other, depending upon the geometry of that cross section). The only remaining thing for the software to do at this stage is to determine the start location for each outline. Since the extrusion nozzle is a finite diameter, this start location is defined by the center of the nozzle. The stop location will be the final point on this trajectory, located approximately one nozzle diameter from the start location. Since it is better to have a slight overlap than a gap and because it is very difficult to precisely control flow, there is likely to be a slight overfill and thus swelling in this start/stop region. If all the start/stop regions are stacked on top of each other, then there will be a “seam” running down the part. In most cases, it is best to have the start/stop regions randomly or evenly distributed around the part so that this seam is not obvious. However, a counter to this may be that a seam is inevitable and having it in an obvious region will make it more straightforward for removing during the post-processing stage.

Determining the fill pattern for the interior of the outlines is a much more difficult task for the control software. The first consideration is that there must be an offset inside the outline and that the extrusion nozzle must be placed inside this outline with minimal overlap. The software must then establish a start location for the fill and determine the trajectory according to a predefined fill pattern. This fill pattern is similar to those used in CNC planar pocket milling where a set amount of material must be removed with a cylindrical cutter [4]. As with CNC milling, there is no unique solution to achieving the filling pattern. Furthermore, the fill pattern may not be a continuous, unbroken trajectory for a particular shape. It is preferable to have as few individual paths as possible but for complex patterns an optimum value may be difficult to establish. As can be seen with even the relatively simple cross section in Fig. 6.3, start and stop locations can be difficult to determine and are somewhat arbitrary. Even with a simpler geometry, like a circle that could be filled continuously using a spiral fill pattern, it is possible to fill from the outside-in or from the inside-out.

Spiral patterns in CNC are quite common, mainly because it is not quite so important as to how the material is removed from a pocket. However, they are less common as fill patterns for extrusion-based additive manufacturing, primarily for the following reason. Consider the example of building a simple solid cylinder. If a spiral pattern were used, every path on every layer would be directly above each other. This could severely compromise part strength and a weave pattern would be much more preferable. As with composite material weave patterning using material like carbon fiber for example, it is better to cross the weave over each other at an angle so that there are no weakened regions due to the directionality in the fibers. Placing extrusion paths over each other in a crossing pattern can help to distribute the strength in each part more evenly.

Every additional weave pattern within a specific layer is going to cause a discontinuity that may result in a weakness within the corresponding part. For complex geometries, it is important to minimize the number of fill patterns used in a single later. As mentioned earlier, and illustrated in Fig. 6.3, it is not possible to ensure that only one continuous fill pattern will successfully fill a single layer. Most outlines can be filled with a theoretically infinite number of fill pattern solutions. It is therefore unlikely that a software solution will provide the best or optimum solution in every case, but an efficient solution methodology should be designed to prevent too many separate patterns from being used in a single layer.

Parts are weakened as a result of gaps between extruded roads. Since weave patterns achieve the best mechanical properties if they are extruded in a continuous path, there are many changes in direction. The curvature in the path for these changes in direction can result in gaps within the part as illustrated in Fig. 6.5. This figure illustrates two different ways to define the toolpath, one that will ensure no additional material will be applied to ensure no part swelling and good part accuracy. The second approach defines an overlap that will cause the material to flow into the void regions, but which may also cause the part to swell. However, in both cases gaps are constrained within the outline material laid down at the perimeter. Additionally, by changing the flow rate at these directional change regions, less or more material can be extruded into these regions to compensate for gaps and swelling. This means that the material flow from the extrusion head should not be directly proportional to the instantaneous velocity of the head when

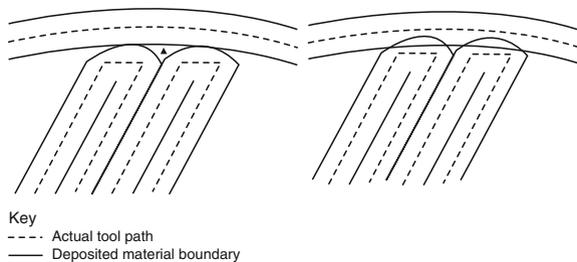


Fig. 6.5 Extrusion of materials to maximize precision (*left*) or material strength (*right*) by controlling voids

the velocity is low, but rather should be increased or decreased slightly, depending on the toolpath strategy used. Furthermore, if the velocity is zero but the machine is known to be executing a directional change in a weave path, a small amount of flow should ideally be maintained. This will cause the affected region to swell slightly and thus help fill gaps. Obviously, care should be taken to ensure that excess material is not extruded to the extent that part geometry is compromised [5].

It can be seen that precise control of extrusion is a complex trade-off, dependent on a significant number of parameters, including:

- Input pressure: This variable is changed regularly during a build, as it is tightly coupled with other input control parameters. Changing the input pressure (or force applied to the material) results in a corresponding output flow rate change. A number of other parameters, however, also affect the flow to a lesser degree.
- Temperature: Maintaining a constant temperature within the melt inside the chamber would be the ideal situation. However, small fluctuations are inevitable and will cause changes in the flow characteristics. Temperature sensing should be carried out somewhere within the chamber and therefore a loosely coupled parameter can be included in the control model for the input feed pressure to compensate for thermal variations. As the heat builds up, the pressure should drop slightly to maintain the same flow rate.
- Nozzle diameter: This is constant for a particular build, but many extrusion-based systems do allow for interchangeable nozzles that can be used to offset speed against precision.
- Material characteristics: Ideally, control models should include information regarding the materials used. This would include viscosity information that would help in understanding the material flow through the nozzle. Since viscous flow, creep, etc. are very difficult to predict, accurately starting and stopping flow can be difficult.
- Gravity and other factors: If no pressure is applied to the chamber, it is possible that material will still flow due to the mass of the molten material within the chamber causing a pressure head. This may also be exacerbated by gaseous pressure buildup inside the chamber if it is sealed. Surface tension of the melt and drag forces at the internal surfaces of the nozzle may retard this effect.
- Temperature build up within the part: All parts will start to cool down as soon as the material has been extruded. However, different geometries will cool at different rates. Large, massive structures will hold their heat for longer times than smaller, thinner parts, due to the variation in surface to volume ratio. Since this may have an effect on the surrounding environment, it may also affect machine control.

Taking these and other factors into consideration can help one better control the flow of material from the nozzle and the corresponding precision of the final part. However, other uncontrollable or marginally controllable factors may still prove problematic to precisely control flow. Many extrusion-based systems, for instance, resort to periodically cleaning the nozzles from time to time to prevent build up of excess material adhered to the nozzle tip.

6.4 Fused Deposition Modeling from Stratasys

By far the most common extrusion-based AM technology is Fused Deposition Modeling (FDM), produced and developed by Stratasys, USA [6]. FDM uses a heating chamber to liquefy polymer that is fed into the system as a filament. The filament is pushed into the chamber by a tractor wheel arrangement and it is this pushing that generates the extrusion pressure. A typical FDM machine can be seen in Fig. 6.6, along with a picture of an extrusion head.

The initial FDM patent was awarded to Stratasys founder Scott Crump in 1992 and the company has gone from strength to strength to the point where there are more FDM machines than any other AM machine type in the world. The major strength of FDM is in the range of materials and the effective mechanical properties of resulting parts made using this technology. Parts made using FDM are amongst the strongest for any polymer-based additive manufacturing process.

The main drawback to using this technology is the build speed. As mentioned earlier, the inertia of the plotting heads means that the maximum speeds and accelerations that can be obtained are somewhat smaller than other systems. Furthermore, FDM requires material to be plotted in a point-wise, vector fashion that involves many changes in direction.

6.4.1 FDM Machine Types

The Stratasys FDM machine range is very wide, from low-cost, small-scale, minimal variable machines through to larger, more versatile, and more sophisticated machines that are inevitably more expensive. The company has separated its operations into subsidiaries, each dedicated to different extents of the FDM technology.

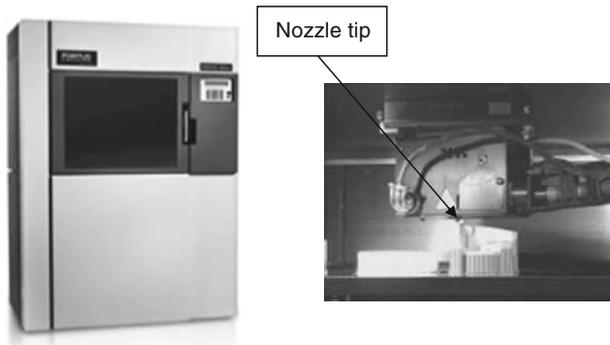


Fig. 6.6 Typical Stratasys machine showing the outside and the extrusion head inside (courtesy of Stratasys)

The first subsidiary, Dimension, focuses on the low-cost machines currently starting around \$15,000 USD. Each Dimension machine can only process a limited range of materials, with only a few user-controllable parameter options. The uPrint machine is currently the smallest and lowest costing machine, with a maximum part size of 6" × 8" × 8". It has only one layer thickness setting and only one build material, with a soluble support system. There are two further machines that are slightly more expensive than the uPrint going upwards in size to 10" × 10" × 12" with different layer thickness settings (0.25 and 0.33 mm) and ABS materials available in multiple colors. More expensive variations use the soluble support material while less expensive machines use a single deposition head and breakaway supports. Finer detail parts can be made using the Elite machine, which has a minimum layer thickness of 0.178 mm. All these machines are designed to operate with minimal setup, variation and intervention. They can be located without special attention to fume extraction and other environmental conditions. This means they can easily be placed in a design office rather than resorting to placing them in a machine shop. Purchasers of Dimension machines would be expected to use them in much the same way as they would an expensive 2D printer.

While Dimension FDM machines can be used for making parts for a wide variety of applications, most parts are likely to be used as concept models by companies investigating the early stages of product development. More demanding applications, like for models for final product approval, functional testing models, and models for direct digital manufacturing, would perhaps require machines that are more versatile, with more control over the settings, more material choices and options that enable the user to correct minor problems in the output model. Higher specification FDM machines are more expensive, not just because of the incorporated technology, but also because of the sales support, maintenance, and reliability. Stratasys has separated this higher-end technology through the subsidiary named FORTUS, with top-of-the-range models costing around \$400,000 USD. The smaller FORTUS 200mc machine starts off roughly where the Dimension machines end, with a slightly smaller build envelope of 8" × 8" × 12" and a similar specification. Further up the range are machines with increases in size, accuracy, range of materials, and range of build speeds. The largest and most sophisticated machine is the FORTUS 900mc, which has the highest accuracy of all Stratasys FDM machines with a layer thickness of 0.076 mm. The build envelope is an impressive 36" × 24" × 36" and there are at least seven different material options.

It should be noted that FDM machines that operate with different layer thicknesses do so because of the use of different nozzle diameters. These nozzles are manually changeable and only one nozzle can be used during a specific build. The nozzle diameter also controls the road width. Obviously, a larger diameter nozzle can extrude more material for a specific plotting speed and thus shorten the build time at the expense of lower precision.

FORTUS software options include the expected file preparation and build setup options. However, there are also software systems that allow the user to remotely monitor the build and schedule builds using a multiple machine setup. Stratasys has

many customers who have purchased more than one machine and their software is aimed at ensuring these customers can operate them with a minimum of user intervention. Much of this support was developed because of another Stratasys subsidiary called Redeye, who use a large number of FDM machines as a service bureau for customers. Much of the operation of Redeye is based on customers logging in to an Internet account and uploading STL files. Parts are scheduled for building and sent back to the customer within a few days, depending on part size, amount of finishing required, and order size.

Stratasys also recognizes that many parts coming off their machines will not be immediately suitable for the final application and that there may be an amount of finishing required. To assist in this, Stratasys provides a range of finishing stations that are designed to be compatible with various FDM materials. Finishing can be a mixture of chemically induced smoothing (using solvents that lightly melt the part surface) or burnishing using sodium bicarbonate as a light abrasive cleaning compound. Also, although there is a range of different material colors for the ABS build material, many applications require the application of primers and coatings to achieve the right color and finish on a part.

6.5 Materials

The most popular material is the ABSplus material, which can be used on all current Stratasys FDM machines. This is an updated version of the original ABS (acrylonitrile butadiene styrene) material that was developed for earlier FDM technology. Users interested in a translucent effect may opt for the ABSi material, which has similar properties to other materials in the ABS range. Some machines also have an option for ABS blended with Polycarbonate. Table 6.1 shows properties for various ABS materials and blends.

These properties are quite similar to many commonly used materials. It should be noted, however, that parts made using these materials on FDM machines may

Table 6.1 Variations in properties for the ABS range of FDM materials (compiled from Stratasys data sheets)

Property	ABS	ABSi	ABSplus	ABS/PC
Tensile strength	22 MPa	37 MPa	36 MPa	34.8 MPa
Tensile modulus	1,627 MPa	1,915 MPa	2,265 MPa	1,827 MPa
Elongation	6%	3.1%	4%	4.3%
Flexural strength	41 MPa	61 MPa	52 MPa	50 MPa
Flexural modulus	1,834 MPa	1,820 MPa	2,198 MPa	1,863 MPa
IZOD impact	106.78 J/m ²	101.4 J/m ²	96 J/m ²	123 J/m ²
Heat deflection @ 66 psi	90°C	87°C	96°C	110°C
Heat deflection @ 264 psi	76°C	73°C	82°C	96°C
Thermal expansion	5.60E-05 in/in/F	6.7E-6 in/in/F	4.90E-05 in/in/F	4.10E-5 in/in F
Specific gravity	1.05	1.08	1.04	1.2

exhibit regions of lower strength than shown in this table because of interfacial regions in the layers and possible voids in the parts.

There are three other materials available for FDM technology that may be useful if the ABS materials cannot fulfill the requirements. A material that is predominantly PC-based can provide higher tensile properties, with a flexural strength of 104 MPa. A variation of this material is the PC-ISO, which is also PC-based, formulated to ISO 10993-1 and USP Class VI requirements. This material, while weaker than the normal PC with a flexural strength of 90 MPa, is certified for use in food and drug packaging and medical device manufacture. Another material that has been developed to suit industrial standards is the ULTEM 9085 material. This has particularly favorable flame, smoke, and toxicity (FST) ratings that makes it suitable for use in aircraft, marine, and ground vehicles. If applications require improved heat deflection, then an option would be to use the Polyphenylsulfone (PPSF) material that has a heat deflection temperature at 264 psi of 189°C. It should be noted that these last three materials can only be used in the high-end machines and that they only work with breakaway support system, making their use somewhat difficult and specialized. The fact that they have numerous ASTM and similar standards attached to their materials indicates that Stratasys is seriously targeting final product manufacture (Direct Digital Manufacturing) as a key application for FDM.

Note that FDM works best with polymers that are amorphous in nature rather than the highly crystalline polymers that are more suitable for PBF processes. This is because the polymers that work best are those that are extruded in a viscous paste rather than in a lower viscosity form. As amorphous polymers, there is no distinct melting point and the material increasingly softens and viscosity lowers with increasing temperature. The viscosity at which these amorphous polymers can be extruded under pressure is high enough that their shape will be largely maintained after extrusion, maintaining the extrusion shape and enabling them to solidify quickly and easily. Furthermore, when material is added in an adjacent road or as a new layer, the previously extruded material can easily bond with it. This is different from Selective Laser Sintering, which relies on high crystallinity in the powdered material to ensure that there is a distinct material change from the powder state to a liquid state within a well-defined temperature region.

6.6 Limitations of FDM

FDM machines made by Stratasys are very successful and meet the demands of many industrial users. This is partly because of the material properties and partly because of the low cost of the entry-level machines. There are, however, disadvantages when using this technology, mainly in terms of build speed, accuracy, and material density. As mentioned earlier, they have a layer thickness option of 0.078 mm, but this is only available with the highest-cost machine and use of this level of precision will lead to longer build times. Note also that all nozzles are

circular and therefore it is impossible to draw sharp external corners; there will be a radius equivalent to that of the nozzle at any corner or edge. Internal corners and edges will also exhibit rounding. The actual shape produced is dependent on the nozzle, acceleration and deceleration characteristics, and the viscoelastic behavior of the material as it solidifies.

The speed of an FDM system is reliant on the feed rate and the plotting speed. Feed rate is also dependent on the ability to supply the material and the rate at which the liquefier can melt the material and feed it through the nozzle. If the liquefier were modified to increase the material flow rate, most likely it would result in an increase in mass. This in turn would make it more difficult to move the extrusion head faster. For precise movement, the plotting system is normally constructed using a lead-screw arrangement. Lower cost systems can use belt drives, but flexing in the belts make it less accurate and there is also a lower torque reduction to the drive motor.

One method to improve the speed of motor drive systems is to reduce the corresponding friction. Stratasys used Magnadrive technology to move the plotting head on early Quantum machines. By gliding the head on a cushion of air counter-balanced against magnetic forces attracting the head to a steel platen, friction was significantly reduced, making it easier to move the heads around at a higher speed. The fact that this system was replaced by conventional ball screw drives in the more recent FORTUS 900mc machine indicates that the improvement was not sufficient to balance against the cost.

One method not tried outside the research labs as yet is the use of a particular build strategy that attempts to balance the speed of using thick layers with the precision of using thin layers. The concept here is that thin layers only need to be used on the exterior of a part. The outline of a part can therefore be built using thin layers, but the interior can be built more quickly using thicker layers. Since most FDM machines have two extruder heads, it is possible that one head could have a thicker nozzle than the other. This thicker nozzle may be employed to build support structures and to fill in the part interior. However, the difficulty in maintaining a correct registration between the two layer thicknesses has probably prevented this approach from being developed commercially. A compromise on this solution is to use a honeycomb (or similar) fill pattern that uses less material and take less time. This is only appropriate for applications where the reduced mass and strength of such a part is not an issue.

An important design consideration when using FDM is to account for the anisotropic nature of a part's properties. Additionally, different layering strategies result in different strengths. For instance, the right-hand scanning strategy in Fig. 6.5 creates stronger parts than the left-hand scanning strategy. Typically, properties are isotropic in the x - y plane, but if the raster fill pattern is set to preferentially deposit along a particular direction, then the properties in the x - y plane will also be anisotropic. In almost every case, the strength in the z -direction is measurably less than the strength in the x - y plane. Thus, for parts which undergo stress in a particular direction it is best to build the part such that the major stress axes are aligned with the x - y plane rather than in the z -direction.

6.7 Bioextrusion

Extrusion-based technology has a large variety of materials that can be processed. If a material can be presented in a liquid form that can quickly solidify, then it is suitable to this process. As mentioned earlier, the creation of this liquid can be either through thermal processing of the material to create a melt, or by using some form of chemical process where the material is in a gel form that can dry out or chemically harden quickly. These techniques are useful for bioextrusion. Bioextrusion is the process of creating biocompatible and/or biodegradable components that are used to generate frameworks, commonly referred to as “scaffolds,” that play host to animal cells for the formation of tissue (tissue engineering). Such scaffolds should be porous, with micro-pores that allow cell adhesion and macro-pores that provide space for cells to grow.

There are a few commercial bioextrusion systems, like the modified FDM process used by Osteopore [7] to create scaffolds to assist in primarily head trauma recovery. This machine uses a conventional FDM-like process with settings for a proprietary material, based on the biocompatible polymer, polycaprolactone (PCL). Most tissue engineering is still, however, in research form; investigating many aspects of the process, including material choice, structural strength of scaffolds, coatings, biocompatibility, and effectiveness within various clinical scenarios. Many systems are in fact developed in-house to match the specific interests of the researchers. There are however a small number of systems that are also available commercially to research labs.

6.7.1 Gel Formation

One common method of creating scaffolds is to use hydrogels. These are polymers that are water insoluble but can be dispersed in water. Hydrogels can therefore be extruded in a jelly like form. Following extrusion, the water can be removed and a solid, porous media remains. Such a media can be very biocompatible and conducive to cell growth with low toxicity levels. Hydrogels can be based on naturally occurring polymers or synthetic polymers. The natural polymers are perhaps more biocompatible whereas the synthetic ones are stronger. Synthetic hydrogels are rarely used in tissue engineering, however, because of the use of toxic reagents. Overall, use of hydrogels results in weak scaffolds that may be useful for soft tissue growth.

6.7.2 Melt Extrusion

Where stronger scaffolds are required, like when used to generate bony tissue, melt extrusion seems to be the process of choice. FDM can be used, but there are some

difficulties in using this approach. In particular, FDM is somewhat unsuitable because of the expense of the materials. Biocompatible polymers suitable for tissue engineering are synthesized in relatively small quantities and are therefore only provided at high cost. Furthermore, the polymers often need to be mixed with other materials, like ceramics, that can seriously affect the flow characteristics, causing the material to behave in a non-Newtonian way. Extrusion using FDM requires the material to be constructed in filament form that is pushed through the system by a pinch roller feed mechanism. This mechanism may not provide sufficient pressure at the nozzle tip, however, and so many of the experimental systems use screw feed, similar to conventional injection molding and extrusion technology. Screw feed systems benefit from being able to feed small amounts of pellet-based feedstock, enabling one to work with a small material volume.

In addition to their layer-wise photopolymerization machines, Envisiontec [8] has also developed the 3D-Bioplotter system (see Fig. 6.7). This system is an extrusion-based, screw feeding technology that is designed specifically for biopolymers. Lower temperature polymers can be extruded using a compressed gas feed, instead of a screw extruder, which results in a much simpler mechanism. Much of the system uses non-reactive stainless steel and the machine itself has a small build envelope and software specifically aimed at scaffold fabrication. The melt chamber is sealed apart from the nozzle, with a compressed air feed to assist the screw extrusion process. The system uses one extrusion head at a time, with a carousel feeder so that extruders can be swapped at any time during the process. This is particularly useful since most tissue engineering research focuses on building scaffolds with different regions made from different materials. Build parameters can be set for a variety of materials with control over the chamber temperature, feed rate, and plotting speed to provide users with a versatile platform for tissue engineering research.

It should be noted that tissue engineering is an extremely complex research area and the construction of physical scaffolds is just the starting point. This approach

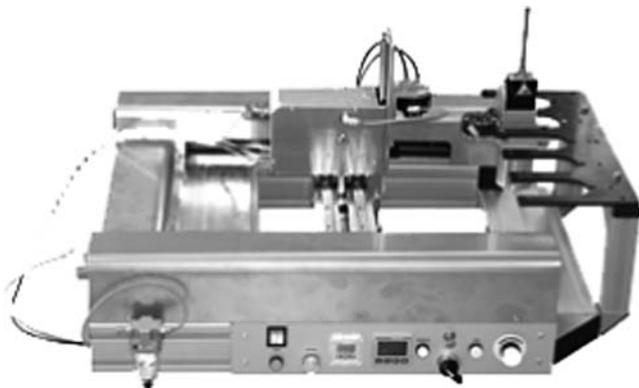


Fig. 6.7 The Envisiontec 3D Bioplotter system (note the multiple head changing system on the right-hand side)

may result in scaffolds that are comparatively strong compared with hydrogel-based scaffolds, but they may fail in terms of biocompatibility and bio-toxicity. To overcome some of these shortcomings, a significant amount of post-processing is required.

6.7.3 Scaffold Architectures

One of the major limitations with extrusion-based systems for conventional manufacturing applications relates to the diameter of the nozzle. For tissue engineering, however, this is not such a limitation. Scaffolds are generally built up so that roads are separated by a set distance so that the scaffold can have a specific macro porosity. In fact, the aim is to produce scaffolds that are as strong as possible but with as much porosity as possible. The greater the porosity, the more space there is for cells to grow. Scaffolds with greater than 66% porosity are common. Sometimes, therefore, it may be better to have a thicker nozzle to build stronger scaffold struts. The spacing between these struts can be used to determine the scaffold porosity.

The most effective geometry for scaffolds has yet to be determined. For many studies scaffolds with a simple 0° and 90° orthogonal crossover pattern may be sufficient. More complex patterns vary the number of crossovers and their separation. Examples of typical patterns can be seen in Fig. 6.8. Much of the studies involve finding out how cells proliferate in these different scaffold architectures and are usually carried out using bioreactors for in-vitro (non-invasive) experiments. As such, samples are usually quite small and often cut from a larger scaffold structure. It is anticipated that it will become commonplace for experiments to be carried out using samples that are as large and complex in shape as the bones they are designed to replace and that are implanted in animal or human subjects. Many more fundamental questions must be answered, however, before this becomes common.

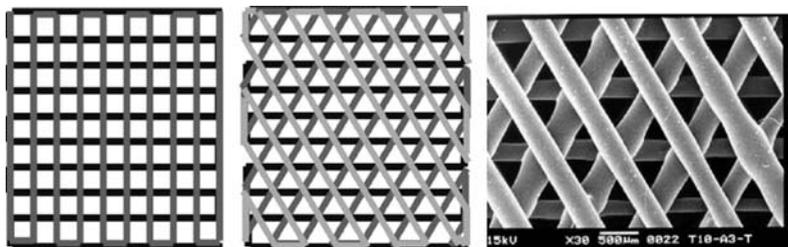


Fig. 6.8 Different scaffold designs showing a porous structure, with an actual image of a scaffold created using a bioextrusion system [14]

6.8 Other Systems

Although Stratasys owns most of the patents on FDM and similar heat-based extrusion technology, there are a number of other such systems commercially available. The majority of these systems can be purchased only in China, until the expiration of Stratasys' patents. The most successful and well-known system is available from the Beijing Yinhua company. Most of these competing FDM machines utilize a screw extrusion system that are fed using powder or pellet feed rather than continuous filaments.

6.8.1 *Contour Crafting*

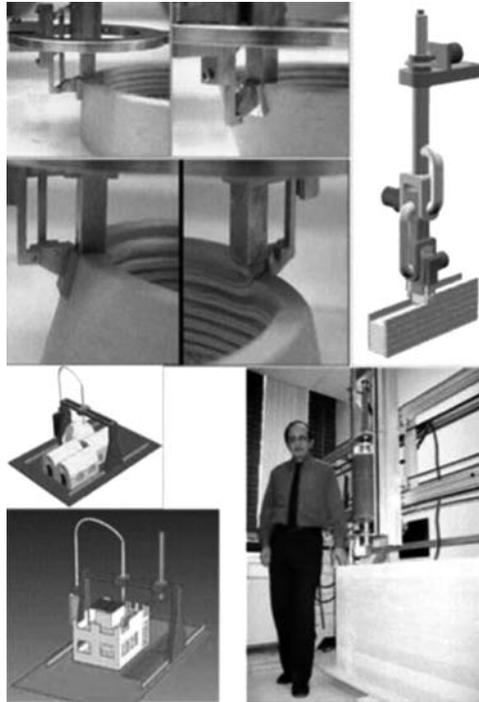
In normal additive manufacturing, layers are considered as 2D shapes extruded linearly in the third dimension. Thicker layers result in lower part precision, particularly where there are slopes or curves in the vertical direction. A major innovative twist on the extrusion-based approach can be found in the Contour Crafting technology developed by Prof. B. Khoshnevis and his team at the University of Southern California [9]. Taking the principle mentioned above that the exterior surface is the most critical in terms of meeting precision requirements, this research team has developed a method to smooth the surface with a scraping tool. This is similar to how artisans shape clay pottery and/or concrete using trowels. By contouring the layers as they are being deposited using the scraping tool to interpolate between these layers, very thick layers can be made that still replicate the intended geometry well.

Using this technique it is conceptually possible to fabricate extremely large objects very quickly compared with other additive processes, since the exterior precision is no longer determined solely by the layer thickness. The scraper tool need not be a straight edge and can indeed be somewhat reconfigurable by positioning different parts of the tool in different regions or by using multiple passes. To illustrate this advantage the team is in fact developing technology that can produce full-sized buildings using a mixture of the Contour Crafting process and robotic assembly (see Fig. 6.9).

6.8.2 *Nonplanar Systems*

There have been a few attempts at developing AM technology that doesn't use stratified, planar layers. The most notable projects are Shaped Deposition Manufacture (SDM), Ballistic Particle Manufacture (BPM), and Curved Laminated Object Manufacture (Curved LOM). The Curved LOM [10] process in particular aims at using fiber-reinforced composite materials, sandwiched together for the purposes of making tough shelled components like nose cones for aircraft using

Fig. 6.9 Contour Crafting technology, developed at USC, showing scraping device and large-scale machine



carbon fiber and armored clothing using Kevlar. To work properly, the layers of material must conform to the shape of the part being designed. If edges of laminates are exposed then they can easily come loose by applying shear forces. The Curved LOM process demonstrated feasibility but also quickly became a very complex system that required conformable robotic handling equipment and high powered laser cutting for the laminates.

It is possible to use short fibers mixed with polymer resins in FDM. Fibers can be extruded so long as the diameter and length of the fibers are small enough to prevent clogging of the nozzles. Like Curved LOM, it is somewhat pointless to use such a material in FDM if the layers are aligned with the build plane. However, if the layers were aligned according to the outer layer of the part, then it may be useful. Parts cannot be built using a flat layer approaching, in this case, and thus process planning for complex geometries becomes problematic. However, certain parts that require surface toughness can benefit from this non-planar approach [11].

6.8.3 FDM of Ceramics

Another possible application of FDM is to develop ceramic part fabrication processes. In particular, FDM can be used to extrude ceramic pastes that can quickly

solidify. The resulting parts can be fired using a high temperature furnace to fuse and densify the ceramic particles. Resulting parts can have very good properties with the geometric complexity characteristics of AM processes. Other AM processes have also been used to create ceramic composites, but most work using FDM came out of Rutgers University in the USA [12].

6.8.4 Reprap and Fab@home

The basic FDM process is quite simple; and this can be illustrated by the development of two systems that are extremely low cost and capable of being constructed using minimal tools.

The Reprap project [13] is essentially an experiment in open source technology. The initial idea was developed by a group at the University of Bath in the UK and designs and ideas are being developed by a number of enthusiasts worldwide. One concept being considered is that a machine is capable of producing components for future machines, testing some of the theories of von Neumann on self-replicating machines. A number of design variants exist, some using cold cure resins and some using a thermal extrusion head, but all are essentially variants of the FDM process, as illustrated by one of these designs shown in Fig. 6.10.

Another project that aims at low-cost FDM technology is the Fab@home concept. This uses a frame constructed from laser-cut polymer sheets, assembled like a 3D jigsaw. Low-cost stepper motors and drives commonly found in ink-jet

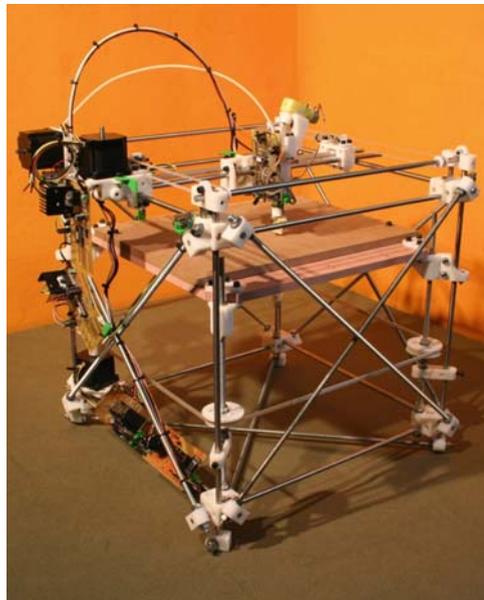


Fig. 6.10 The RepRap “Darwin” machine that is capable of making some of its own parts

printers are used for positioning and the extrusion head is normally a compressed-air-fed syringe that contains a variety of cold-cure materials. The Fab@home designs can be obtained free of charge and kits can be obtained for assembly at a very low cost.

Both of these approaches have inspired a variety of enthusiasts to develop their ideas. Some have focused on improving the designs so that they may be more robust or more versatile. Others have developed software routines that explore things like scanning patterns, more precise control, etc. Yet other enthusiasts have developed new potential applications for this technology, most notably using multiple materials that have unusual chemical or physical behavior. The Fab@home technology has, for example, been used to develop 3D batteries and actuators. Some users have even experimented with chocolate to create edible sculptures.

6.9 Exercises

1. Derive an expression for Q_T so that we can determine the flow through a circular extrusion nozzle.
2. The expression for total flow does not include a gravity coefficient. Derive an expression for Q_T that includes gravity, assuming there is a constant amount of material in the melt chamber and the nozzle is pointing vertically downwards.
3. The expressions derived for solidification and bonding assume that a thermal process is being used. What do you think the terms will look like if a curing or drying process were used?
4. Why is extrusion-based AM more suitable for medical scaffold architectures, compared with SLS-fabricated scaffolds made from a similar material?
5. In what ways is extrusion-based AM similar to CNC pocket milling and in what ways is it different?

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