Part IX Special Processing and Assembly Technologies

32 Rapid Prototyping and Additive Manufacturing

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In this part of the book, a collection of processing and assembly technologies is discussed that do not fit neatly into the classification scheme in Figure 1.5. They are technologies that have been adapted from conventional manufacturing and assembly operations or developed from scratch to serve special functions or needs in design and manufacturing. Rapid prototyping and additive manufacturing, covered in the present chapter, are a collection of processes used to fabricate parts directly from a computer-aided design (CAD) model. Chapters 33 and 34 discuss technologies used in electronics manufacturing, an activity of significant economic importance. Chapter 33 covers integrated circuit processing, and Chapter 34 covers electronics assembly and packaging. Chapters 35 and 36 survey some of the technologies used to produce very small parts and products. Chapter 35 describes microfabrication technologies used to produce items measured in microns (10^{-6} m), whereas Chapter 36 discusses nanofabrication technologies for producing items measured in nanometers (10^{-9} m). The processes covered in these five chapters are relatively new. Rapid prototyping dates from about 1988. Modern electronics production techniques date from around

1960 (Historical Note 33.1), although dramatic advances have been made in electronics processing since that time. The microfabrication technologies discussed in Chapter 35 followed soon after integrated circuit processing. Finally, nanofabrication represents an emerging field today that dates from the 1990s.

Rapid prototyping (RP) is a family of technologies used to fabricate engineering prototypes of parts in minimum possible lead time based on a computer-aided design (CAD) model of the item. The traditional method of fabricating a prototype part is machining, which can require significant lead times—up to several weeks, sometimes longer, depending on part complexity, difficulty in ordering materials, and scheduling production equipment. A number of rapid prototyping techniques are now available that allow a part to be produced in hours or days rather than weeks, given that a computer model of the part has been generated on a CAD system.

As the RP technologies have evolved, they are increasingly being used to produce parts, not just prototypes, and a more general term has emerged: ***Additive manufacturing*** (AM), which refers to the same technologies used in RP. All of these technologies work by adding layers of material to an existing part or substrate, so that the item is gradually built one layer at a time; hence the word "additive." One might say that rapid prototyping is a subset of additive manufacturing when the purpose is to fabricate a physical model of a newly designed part. Other terms often used synonymously with AM include direct digital manufacturing, rapid manufacturing, layer-based manufacturing, and solid free-form fabrication. A short history of rapid prototyping and additive manufacturing is presented in Historical Note 32.1.

Historical Note 32.1 *Rapid Prototyping and Additive Manufacturing (4)*

It should be noted that the historical development of rapid prototyping and additive manufacturing is based on several enabling technologies, including integrated circuits, computers, in particular computer graphics and computer-aided design, lasers, ink-jet and other printing technologies, and highly accurate positioning systems, to name the most obvious. Without these enablers, RP and AM would not be technically feasible.

The beginnings of rapid prototyping as an identifiable technical area occurred in the mid-1980s when similar patents were filed by researchers in Japan, France, and the United States. What these patent applications had in common was the idea of constructing a three-dimensional object by adding a sequence of layers, one on top of the previous. The patent by Charles Hull is considered the most significant because it resulted in the commercial development of stereolithography (SL) and the formation of the company 3D Systems, Inc. SL users a laser beam to harden liquid photopolymers in a layer by layer construction process.

Several additional patents followed in 1986 for Solid Ground Curing (SGC, Section 32.2.1); Selective Laser Sintering (SLS, Section 32.2.2); and Laminated Object Manufacturing (LOM, Section 32.2.4). SGC exposed photopolymers through a physical mask; SLS used lasers to sinter or melt powder layers; and LOM cut paper sheets in the part building procedure. These systems were commercially introduced by three start-up companies, respectively, Cubital, DTM, and Helisys. DTM was the only survivor; it merged with 3D Systems in 2001.

In 1989, Fused Deposition Modeling (FDM, Section 32.2.3) was patented, and the Stratasys Company was formed to commercialize the technology. FDM uses an extrusion process to add layers of material to an existing structure. In the same year, Three-Dimensional Printing (3DP, Section 32.2.2), which uses ink-jets to deposit droplets of a binder onto layers of powdered material, was patented by researchers at MIT. They licensed the technology to several companies for development and commercialization. In 1994, a similar approach based on ink-jet technology was developed, only it deposits the material itself to form layers rather than a binder on powder.

The collection of processes discussed here, with refinements over many years, constitute the majority of the RP and AM technologies used today throughout the world. Even SGC and LOM are used in altered forms, although the companies that originally developed them were unsuccessful.

32.1 Fundamentals of Rapid Prototyping and Additive Manufacturing

The special need that motivated the development of rapid prototyping is that product designers would like to have a physical model of a new part design rather than a computer model or line drawing. The creation of a prototype is an integral step in the design procedure. A ***virtual prototype***, which is a computer model of the part design on a CAD system, may not be adequate for the designer to visualize the part. It certainly is not sufficient to conduct real physical tests on the part, although it is possible to perform simulated tests by finite element analysis or other methods. Using one of the available RP technologies, a solid physical part can be created in a relatively short time (hours if the company possesses the RP equipment or days if the part fabrication must be contracted to an outside firm specializing in RP). The designer can therefore visually examine and physically feel the part and begin to perform tests and experiments to assess its merits and shortcomings. By speeding up the process of fabricating part prototypes, the duration of the entire product design cycle is reduced.

Available prototyping technologies can be divided into two basic categories: (1) material removal processes, and (2) material addition processes. The ***material removal RP*** alternative involves machining, primarily milling and drilling, using a dedicated Computer Numerical Control (CNC) machine that is available to the design department on short notice. To use CNC, a part program must be prepared from the CAD model (Section 37.3.3). The starting material is often a solid block of wax, which is very easy to machine, and the part and chips can be melted and resolidified for reuse when the current prototype is no longer needed. Other starting materials can also be used, such as wood, plastics, or metals (e.g., a machinable grade of aluminum or brass). The CNC machines used for rapid prototyping are often small, and the terms ***desktop milling*** or ***desktop machining*** are sometimes used when referring to them.

The principal emphasis in this chapter is on ***material-addition*** technologies, all of which add thin layers of material one at a time to build the physical part from bottom to top. Advantages of these technologies over CNC machining include [4]: (1) speed of part delivery, as has already been mentioned; (2) avoidance of the CNC part programming task, because the CAD model is the part program in RP; and (3) complexity of part geometry is not an issue in additive manufacturing. Considering this last point, the AM time advantage increases with the complexity of the part geometry, because additive technologies operate the same whether the part is simple or complex, whereas CNC planning must include decisions about tooling, sequence, and access, and more machining is generally required for more complex parts.

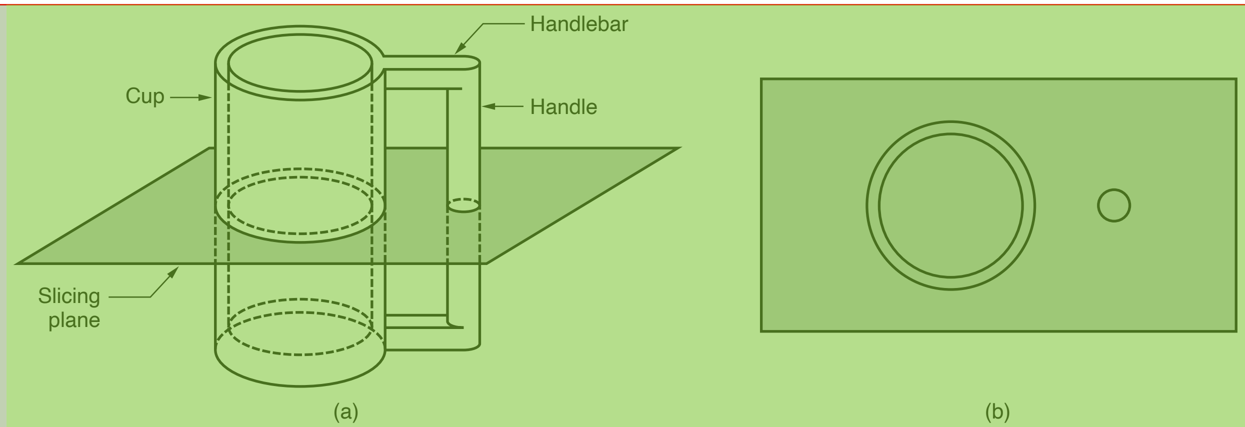

FIGURE 32.1 Conversion of a solid model of an object into layers (only one layer is shown).

The common approach to prepare the control instructions (i.e., part program) in all of the rapid prototyping and additive manufacturing technologies involves the following steps [7]:

1. ***Geometric modeling***. This consists of modeling the component on a CAD system to define its enclosed volume. Solid modeling is the preferred technique because it provides a complete and unambiguous mathematical representation of the geometry. The important issue is to distinguish the interior (mass) of the part from its exterior, and solid modeling provides for this distinction.
2. ***Tessellation of the geometric model***.[1] In this step, the CAD model is converted into a format that approximates its surfaces by triangles, with their vertices arranged to distinguish the object's interior from its exterior. The common tessellation format used in rapid prototyping is STL[2], which has become the de facto standard input format for nearly all RP systems.
3. ***Slicing of the model into layers***. In this step, the model in STL file format is sliced into closely spaced parallel horizontal layers. Conversion of a solid model into layers is illustrated in Figure 32.1. These layers are subsequently used by the RP system to construct the physical model. By convention, the layers are formed in the *x-y* plane, and the layering procedure occurs in the *z*-axis direction. For each layer, a curing path is generated, called the STI file, which is the path that will be followed by the RP system to cure (or otherwise solidify) the layer.

Starting material forms in additive manufacturing include (1) liquid polymers that are cured layer by layer into solid polymers, (2) powders that are aggregated and bonded layer by layer, (3) molten materials that are solidified layer by layer, and (4) solid sheets that are laminated to create the solid part. Material types include wax, polymers, metals, and ceramics.

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[1] More generally, the term ***tessellation*** refers to the laying out or creation of a mosaic, such as one consisting of small colored tiles affixed to a surface for decoration.
[2] STL stands for STereoLithography, one of the primary systems used for rapid prototyping, developed by 3D Systems, Inc.

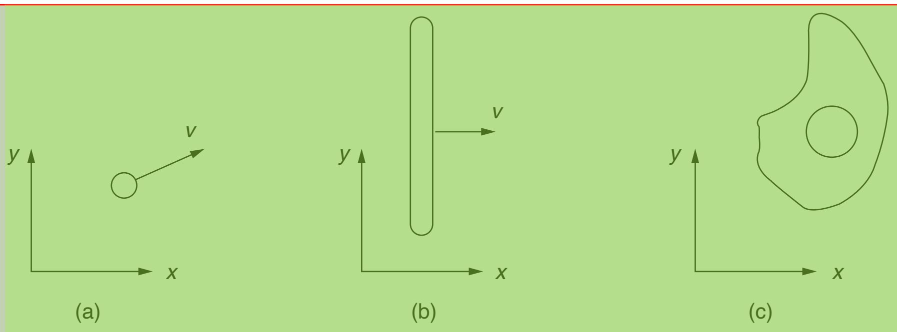

FIGURE 32.2 The three basic layer construction modes: (a) point or spot mode, (b) moving line mode, and (c) layer mode.

In addition to starting material, there are various layer-forming processes by which each layer is created to build the part. These processes include (1) lasers, (2) printing heads that operate using ink-jet technology, and (3) extruder heads. Other processes are based on electron beams, cutting knives, ultraviolet light systems, and so on.

In addition to the layer forming process, several modes of operation are used, called channel modes. The three basic channel modes are (1) a moving point or moving spot; for example, a laser spot moving in an *x-y* plane to chemically solidify a layer of liquid polymer by photopolymerization; (2) a moving line consisting of a linear array of spots that sweeps across the entire layer in one translational motion, somewhat like the way ink-jet printers work; and finally (3) a layer mode using a mask projection system in which the entire layer is created all at the same time. The time to complete each layer can be significant using the moving-point mode. The moving line mode of operation is faster, and the layer mode is theoretically the fastest. The three channel modes are depicted in Figure 32.2.

A summary of these combinations of starting material forms and types, layer-forming processes, and channel modes is presented in Table 32.1 together with representative AM systems.

TABLE • 32.1 Additive Manufacturing Starting Materials, Layer-Forming Processes, and Channel Modes.

Starting material form	RP/AM system	Typical material types	Layer-forming process	Channel mode
Liquid polymer	SL	Photopolymer	Laser curing	Moving point
	MPSL	Photopolymer	Laser curing	Layer-wide
Powders	SLS	Polymers, metals	Laser melting or sintering	Moving point
	3DP	Binder applied to polymer powders	Droplet-based printing head	Moving line
Molten material	FDM	Polymers, wax	Extruder head	Moving point
	DDM	Polymers, wax, low melting point metals	Droplet-based printing head	Moving point or moving line
Solid sheets	LOM	Paper or polymer	Laser or knife	Moving point

Key: SL = stereolithography, MPSL = mask projection stereolithography, SLS = selective laser sintering, 3DP = three-dimensional printing, FDM = fused deposition modeling, DDM = droplet deposition manufacturing, LOM = laminated object manufacturing.

32.2 Additive Manufacturing Processes

AM processes can be classified in various ways. The classification system used here is based on the form of the starting material in the process: (1) liquid-based, (2) powder-based, (3) molten material, and (4) solid sheets. These starting materials are subjected to the various layer-forming processes and channel modes.

32.2.1 LIQUID-BASED SYSTEMS

The starting material in these processes is a liquid polymer. Stereolithography is the main technology in this category, although it includes several variations, one of which is discussed here.

Stereolithography This was the first material addition RP technology, dating from about 1988 and introduced by 3D Systems Inc. based on the work of inventor Charles Hull. It is one of the most widely used additive manufacturing methods. Stereolithography (SL) is a process for fabricating a solid plastic part out of a photosensitive liquid polymer using a directed laser beam to solidify the polymer. The general setup for the process is illustrated in Figure 32.3. Part fabrication is accomplished as a series of layers, in which one layer is added onto the previous layer to gradually build the desired three-dimensional geometry. A part fabricated by SL is illustrated in Figure 32.4.

The stereolithography apparatus consists of (1) a platform that can be moved vertically inside a vessel containing the photosensitive polymer, and (2) a laser whose beam can be controlled in the *x-y* direction. At the start of the process, the platform is positioned vertically near the surface of the liquid photopolymer, and the laser beam is directed through a curing path that comprises an area corresponding to the base (bottom layer) of the part. This and subsequent curing paths are defined by the STI file (step 3 in preparing the control instructions described earlier). The action of the laser is to harden (cure) the photosensitive polymer where the beam strikes the liquid, forming a solid layer of plastic that adheres to

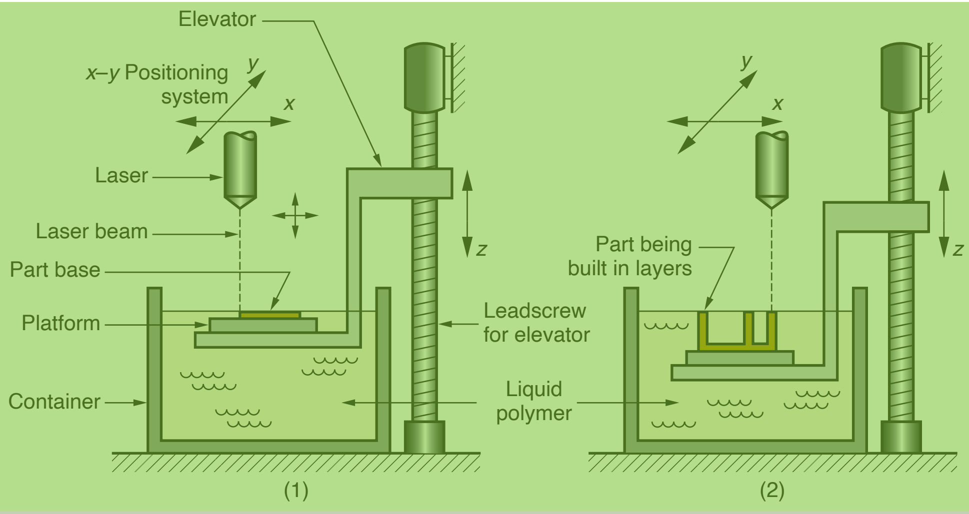

FIGURE 32.3 Stereolithography: (1) at the start of the process, in which the initial layer is added to the platform; and (2) after several layers have been added so that the part geometry gradually takes form.

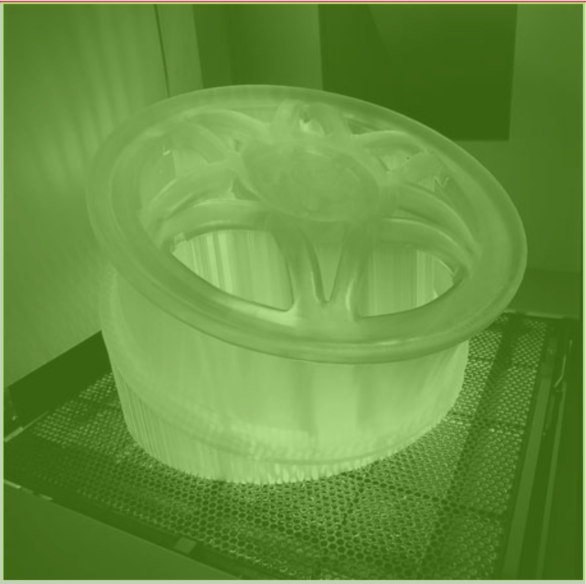

FIGURE 32.4 A part produced by stereolithography. (Photo courtesy of 3D Systems, Inc.)

the platform. When the initial layer is completed, the platform is lowered by a distance equal to the layer thickness, and a second layer is formed on top of the first by the laser, and so on. Before each new layer is cured, a recoating blade is passed over the viscous liquid resin to ensure that its level is the same throughout the surface. Each layer consists of its own area shape, so that the succession of layers, one on top of the previous, creates the solid part shape. Typical layer thickness is 0.05 to 0.15 mm (0.002–0.006 in). Thinner layers provide better resolution and allow more intricate part shapes; but processing times are longer. Typical liquid photopolymers include acrylic and epoxy, which are cured upon exposure to an ultraviolet laser. After all of the layers have been formed, excess polymer is removed, and light sanding is sometimes used to improve smoothness and appearance.

Depending on its design and orientation, a part may contain overhanging features that have no means of support during the bottom-up approach used in stereolithography. For example, in Figure 32.1, if the lower half of the handle and the lower handlebar were eliminated, the upper portion of the handle would be unsupported during fabrication. In these cases, extra pillars or webs may need to be added to the part simply for support purposes. Otherwise, the overhangs may float away or otherwise distort the desired part geometry. These extra features must be trimmed away after the process is completed.

Mask Projection Stereolithography Conventional stereolithography described above uses a single moving laser beam to cure the photopolymer in a given layer. As mentioned, this can be quite time consuming. In mask projection stereolithography (MPSL), the entire layer of liquid photopolymer is exposed at once to an ultraviolet light source through a mask instead of using a scanning laser beam. The hardening process for each layer in MPSL is therefore much shorter than conventional SL.

The key to MPSL is the use of a dynamic mask that is digitally altered for each layer by any of several proprietary technologies such as the digital micromirror device™ (DMD), a product of Texas Instruments [14]. A DMD is an integrated

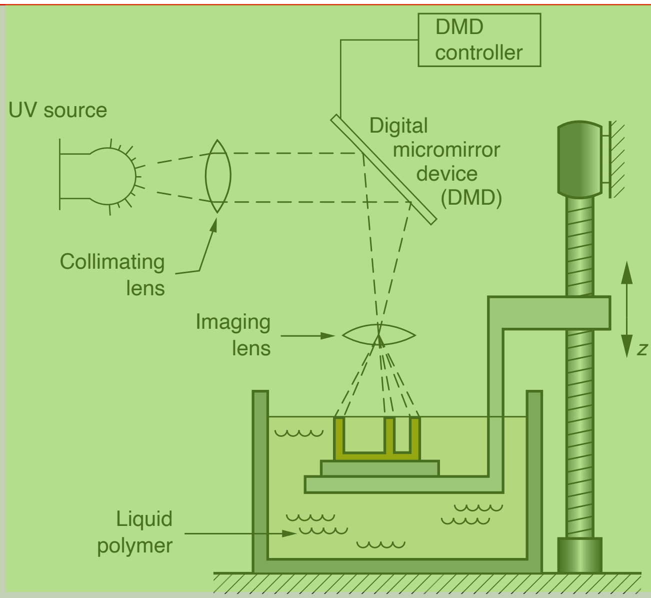

FIGURE 32.5 Mask Projected Stereolithography uses a layer mode.

circuit plus additional hardware consisting of several hundred thousand aluminum mirrors arranged in a rectangular pattern. The mirrors, which are only about 16 μm (0.00063 in) across, can be individually rotated between on and off states corresponding to the bright and dark pixels in the dynamic mask. Light from a UV source is focused on the DMD which reflects the mask image corresponding to the programmed layer pattern onto the liquid polymer.[3] The mask projection stereolithography process is depicted in Figure 32.5.

32.2.2 POWDER-BASED SYSTEMS

The common feature of the additive manufacturing processes described below is that the starting material is powder.[4] These processes are sometimes referred to by the name ***Powder Bed Fusion***, all of which operate on a bed of powdered material [4]. Two important AM processes in this category are (1) selective laser sintering and (2) three-dimensional printing.

Selective Laser Sintering Selective laser sintering (SLS) uses a moving laser beam to fuse powders in areas corresponding to the CAD geometric model one layer at a time to build the solid part. After each layer is completed, a new layer of loose powders is spread across the surface and leveled using a counter-rotating roller. The powders are preheated to just below their melting point to facilitate

[3] It is of interest to note that the precursor of MPSL was developed in 1986 called Solid Ground Curing (SGC, Historical Note 32.1). SGC was ultimately unsuccessful because it used a physical mask rather than a dynamic mask as in MPSL. A new mask had to be fabricated for each new layer in SGC, which made the technology uncompetitive compared with other RP and AM technologies.

[4] The definition, characteristics, and production of powders are described in Chapters 15 and 16.

bonding and reduce distortion of the finished product. Preheating also serves to reduce power requirements of the laser. Layer by layer, the powders are gradually bonded into a solid mass that forms the three-dimensional part geometry. In areas not sintered by the laser beam, the powders remain loose so they can be poured out of the completed part. Meanwhile, they serve to support the solid regions of the part as fabrication proceeds. Layer thickness is 0.075 to 0.50 mm (0.003–0.020 in). The SLS process is usually accomplished in an enclosure that is filled with nitrogen to minimize degradation of powders that might be susceptible to oxidation (e.g., metals).

SLS was developed by Carl Deckard at the University of Texas (Austin) as an alternative to stereolithography, and SLS machines were originally marketed by DTM Corporation, a company founded by Deckard and two partners [9].[5] It is a more versatile process than stereolithography in terms of possible work materials. Whereas SL is limited to liquid photopolymers, selective laser sintering materials include polymers, metals, and ceramics, which are generally less expensive than photosensitive resins.

As mentioned, SLS is a Powder Bed Fusion (PBF) process. Other PBF technologies differ from SLS in the following ways: (1) heating or fusion techniques, (2) methods for handling the powders, and (3) mechanisms by which the powders are bonded into solid objects. For example, one alternative process uses an electron beam as the heating source to melt the powders; it is called electron beam melting (EBM). Other variations include the use of line-wise and layer-wise processes as opposed to the point-wise process in selective laser sintering.

Three-Dimensional Printing This technology (3DP) builds the part using an ink-jet printer to eject adhesive bonding material onto successive layers of powders. The binder is deposited in areas corresponding to the cross sections of the solid part, as determined by slicing the CAD geometric model into layers. The binder holds the powders together to form the solid part, whereas the unbonded powders remain loose to be removed later. While the loose powders are in place during the build process, they serve to support overhanging and fragile features of the part. When the build process is complete, the loose powders are removed. To further strengthen the part, a sintering step can be applied to bond the individual powders.

The part is built on a platform whose level is controlled by a piston. Consider the process for one cross section with reference to Figure 32.6: (1) A layer of powder is spread on the existing part-in-process. (2) An ink-jet printing head moves across the surface using a line-wise channel mode, ejecting droplets of binder on those regions that are to become the solid part. (3) When the printing of the current layer is completed, the piston lowers the platform for the next layer.

Starting materials in 3DP are powders of ceramic, metal, or cermet, and binders that are polymeric or colloidal silica or silicon carbide [12], [19]. Typical layer thickness ranges from about 0.10 to 0.20 mm (0.004–0.008 in). The ink-jet printing head moves across the layer at a speed of about 1.5 m/sec (59 in/sec), with ejection of liquid binder determined during the sweep by raster scanning. The sweep time, together with the spreading of the powders, permits a cycle time per layer of about 2 seconds [19]. Allowing for repositioning and recoating delays, this permits the machine to operate at a rate of two to four layers per minute [4].

[5] The initials DTM stand for desktop manufacturing [9]. DTM merged with 3D Systems in 2001 [4].

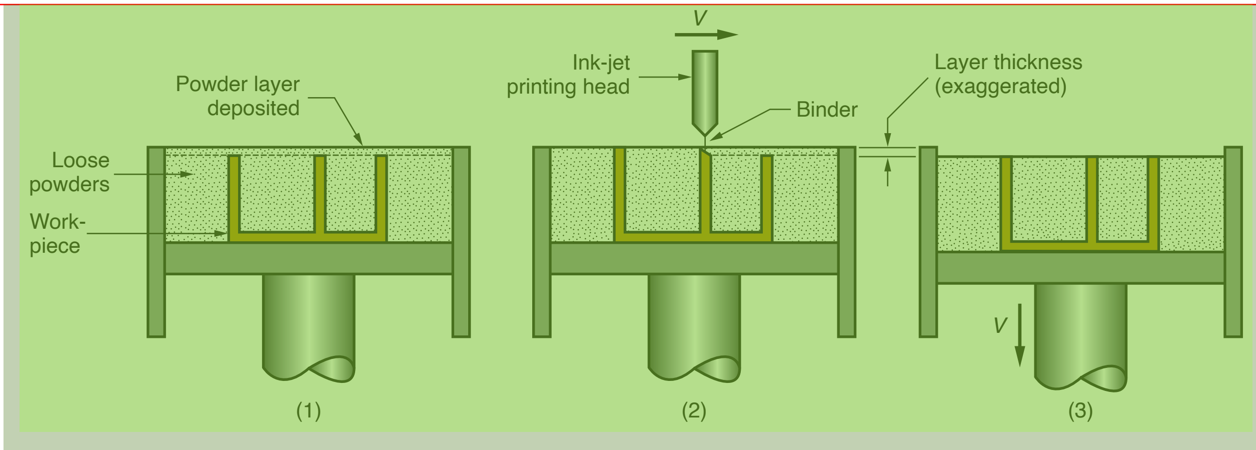

FIGURE 32.6 Three-dimensional printing: (1) powder layer is deposited, (2) ink-jet printing of areas that will become the part, and (3) piston is lowered for next layer (key: v = motion).

32.2.3 MOLTEN MATERIAL SYSTEMS

These additive technologies work by depositing material onto the layer at close to the material's melting point. Although the material is molten just before deposition, it must be in a solid or semisolid state immediately after it is deposited to maintain the desired shape. As a practical matter, the melting requirement limits the materials that can be used with these systems to thermoplastic polymers or wax. Two representative systems are described below: (1) fused deposition modeling, which uses an extrusion head to dispense the material; and (2) droplet deposition manufacturing, which uses a multichannel printing head.

Fused-Deposition Modeling Fused-deposition modeling (FDM) is an RP process in which a filament of wax and/or thermoplastic polymer is extruded onto the existing part surface from a work head to complete each new layer. The work head is controlled in the *x-y* plane during each layer and then moved up by a distance equal to one layer in the *z*-direction. The starting material is a solid filament with typical diameter = 1.25 mm (0.050 in) fed from a spool into the work head, which heats the material to about 0.5°C (~1°F) above its melting point before extruding it onto the part surface. The extrudate is solidified and cold welded to the cooler part surface in about 0.1 sec. If a support structure is needed, that material is usually extruded by a second extrusion head using a different material that can be readily separated from the main part. The part is fabricated from the base up, using a layer-by-layer procedure similar to other RP systems. A disadvantage of FDM is its relatively slow speed, because the deposited material is applied in a moving-point channel mode, and the work head cannot be moved with the high speed of a laser spot. Also, the use of an extruder, with its circular nozzle orifice, makes it difficult to form sharp corners [4].

FDM was developed by Stratasys Inc., which sold its first machine in 1990. Today, there are more FDM machines throughout the world than any other type of AM machine [4]. The starting data is a CAD geometric model that is processed by Stratasys's software modules QuickSlice®; and SupportWork™. QuickSlice® is used to slice the model into layers, and SupportWork™ is used to generate any support

FIGURE 32.7 Collection of parts produced by fused deposition modeling. (Courtesy of George E. Kane Manufacturing Technology Laboratory, Lehigh University.)

structures that are required during the build process. The slice (layer) thickness is typically set from 0.25 to 0.33 mm (0.01–0.013 in), but for finer details, layer thickness can be set to a minimum of 0.076 mm (0.003 in) [4]. Up to about 400 mm of filament can be deposited per second by the extrusion work head. Starting materials are wax and several polymers, including ABS and polycarbonate. These materials are nontoxic, allowing the FDM machine to be set up in an office environment. A collection of plastic parts made by fused deposition modeling is shown in Figure 32.7, and the FDM machine that made these parts is shown in Figure 32.8.

Droplet Deposition Manufacturing This process, also known as ballistic-particle manufacturing, operates by melting the starting material and shooting small droplets onto a previously formed layer. The term droplet deposition manufacturing (DDM) refers to the fact that small particles of work material are deposited as projectile droplets from the work head nozzle. The liquid droplets cold weld to the surface to form a new layer. The deposition of droplets for each new layer is controlled by a moving *x-y* work head that operates in a point-wise manner, in which the path is based on a cross section of a CAD geometric model that has been sliced into layers. For geometries that require a support structure, two work heads are used, one to dispense the polymer to make the object itself, and the second to deposit another material for the support. After each layer has been applied, the platform supporting the part is lowered a certain distance corresponding to the layer thickness, in preparation for the next layer.

Several commercial additive manufacturing machines are based on this general operating principle, the differences being in the type of material that is deposited

FIGURE 32.8 Fused deposition modeling machine. (Courtesy of George E. Kane Manufacturing Technology Laboratory, Lehigh University.)

and the corresponding technique by which the work head operates to melt and apply the material. An important criterion that must be satisfied by the starting material is that it be readily melted and solidified. Work materials used in DDM include wax and thermoplastics. Metals with low melting point, such as tin and aluminum, have also been tested. Improvements in the channel modes include the use of moving line printing heads that operate much like ink-jet printers.

32.2.4 SOLID SHEET–BASED SYSTEMS

The common feature in these additive manufacturing systems is that the starting material is a solid sheet. In this section a solid-sheet system called laminated-object manufacturing is discussed. Differences among commercial products in this category include materials out of which the sheets are made and methods of assembling the sheets.

Laminated-Object Manufacturing Laminated-object manufacturing (LOM) produces a solid physical model by stacking layers of sheet stock that are each cut to an outline corresponding to the cross-sectional shape of a CAD model that has been sliced into layers. The layers are sequentially stacked and bonded one on top of the previous one to build the part. After cutting, the excess material in each layer remains in place to support the part during building. Starting materials in LOM include paper, cardboard, and plastic in sheet stock form. Stock thickness is 0.05 to 0.50 mm (0.002–0.020 in). In LOM, the sheet material is usually supplied with adhesive backing as rolls that are spooled between two reels, as in Figure 32.9. Otherwise, the LOM process must include an adhesive coating step for each layer.

The data preparation phase in LOM consists of slicing the geometric model using the STL file for the given part. With reference to Figure 32.9, the LOM process for each layer can be described as follows, picking up the action with a sheet of stock in place and bonded to the previous stack: (1) The cross-sectional perimeter of the STL model is computed based on the measured height of the physical part at the current layer of completion. The slicing function in LOM is performed after each layer has been physically added and the vertical height of the part has been measured. This provides a feedback correction to account for the actual thickness of the sheet stock being used, a feature unavailable on most other RP systems. (2) A laser beam is used to cut along the perimeter, as well as to crosshatch the surplus portions of the sheet for subsequent removal. The cutting trajectory is controlled by means of an x-y positioning system, and cutting depth is controlled so that only the top layer is cut. (3) The platform holding the stack is lowered, and the sheet stock is advanced between supply roll and take-up spool for the next layer. The platform is then raised to a height consistent with the stock thickness, and a heated roller moves across the new layer to bond it to the previous layer. The height of the physical stack is measured in preparation for the next slicing computation.

When all of the layers are completed, the new part is separated from the excess external material. The part can then be sanded to smooth and blend the layered edges. A sealing application is recommended, at least for paper and cardboard stock to prevent moisture absorption and damage, using a urethane, epoxy, or other polymer spray. LOM part sizes can be relatively large among AM processes, with work volumes up to 800 mm × 500 mm by 550 mm (32 in × 20 in × 22 in). More common work volumes are 380 mm × 250 mm × 350 mm (15 in × 10 in × 14 in).

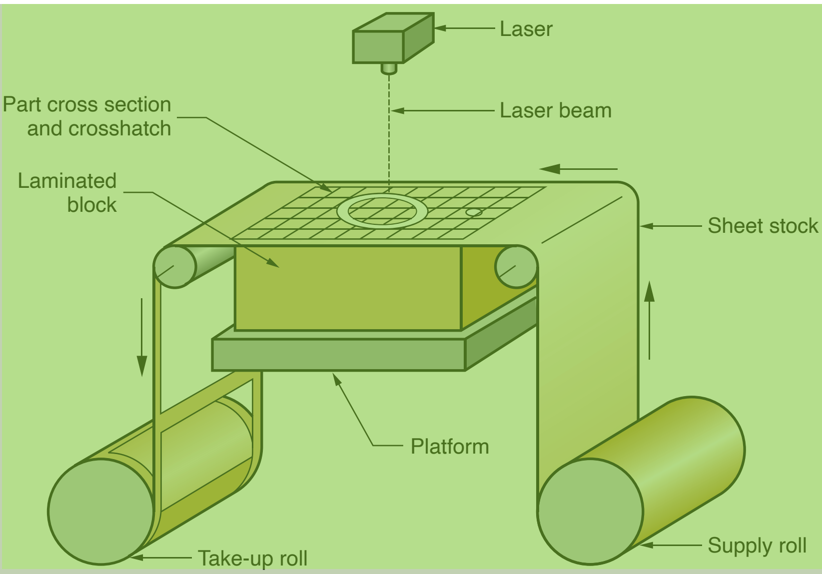

FIGURE 32.9 Laminated-object manufacturing.

Thus, one of the advantages of LOM compared to other RP and AM technologies is the capability to build parts that are quite large.

The original company offering LOM systems was Helisys, Inc. Its machine processed paper sheet stock backed with adhesive and used a sequence in which the most recently added sheet was bonded to the existing structure before cutting the outline in that layer. A heated roller was used to melt the thermoplastic adhesive in the bonding operation. Subsequent modifications in LOM introduced by other companies have included (1) the use of a cutting blade rather than a laser to perform the cutting, (2) polymeric sheet stock rather than paper as the material, and (3) changing the process sequence to cut the layer outline before bonding rather than bonding before cutting. The advantage of this last modification is that it facilitates the fabrication of objects that possess internal features [4].

32.3 Cycle Time and Cost Analysis

All of the additive manufacturing technologies described above work in a similar way, which is to build a part or prototype by adding layers one layer at a time. The purpose of this section is to develop mathematical models of this layer-by-layer approach to determine cycle time and part cost.

Cycle Time Analysis The cycle time to build a part by the layering processes in additive manufacturing depends on the size of the part (volume of material in the part) and the number of parts produced in one build cycle. It also depends on the layer formation processes (e.g., lasers, droplet-based, extruder) and the associated channel mode (moving spot, moving line, or layer). Associated process parameters include layer thickness (thinner layers mean more layers and slower cycle time for the same part size), the speed with which the moving spot or moving line travels, and any delays that are inherent in the process, such as repositioning and recoating. The modeling approach used here for estimating build time is to determine the time to complete each layer and then sum up the layer times to obtain the overall cycle time. An alternative and more detailed approach is described in Gibson et al [4].

First, the time to complete a single layer in processes that use a moving-spot channel mode is given by the following equation:

$$T_i = \frac{A_i}{vD} + T_r \tag{32.1}$$

where T_i = time to complete layer i, s (sec), where the subscript i is used to identify the layer; A_i = area of layer i, mm^2 (in^2); v = speed of the moving spot on the surface, mm/s (in/sec); D = diameter of the spot (assumed circular), mm (in); and T_r = repositioning and recoating time between layers, s (sec). Repositioning time involves lowering the worktable to prepare for the next layer to be fabricated. It also includes repositioning of the work head at the beginning and end of a layer if that is not performed in parallel with table repositioning. Recoating time is the time to spread material for the new layer; for example, to spread the next layer of powders. Recoating time is not applicable in all AM processes. T_r may also include built-in delays associated with each layer, such as cooling or heating delays, and nozzle cleaning.

Once the T_i values have been determined for all layers, then the build cycle time can be determined as the sum of these times plus any setup or start-up time required for the process. For example, the machine may require a warm-up period during which the chamber is brought up to a specified temperature. It may also be desirable to include the time for the operator to load the starting material and perform any setup tasks that are associated with the production run. The total cycle time is given by the following:

$$T_c = T_{su} + \sum_{i=1}^{n_l} T_i \tag{32.2}$$

where T_c = build cycle time, s (sec); T_{su} = setup time, s (sec); and n_l = number of layers used to approximate the part.

Example 32.1 Build cycle time in stereolithography

The square cup-shaped part shown in Figure 32.10 is to be fabricated using stereolithography. The base of the cup is 40 mm on each side and is 5 mm thick. The walls are 4 mm thick, and the total height of the cup = 52 mm. The SL machine used for the job uses a spot diameter = 0.25 mm, and the beam is moved at a speed = 950 mm/s. Layer thickness = 0.10 mm. Repositioning and recoating time for each layer = 21 s. Compute an estimate of the cycle time to build the part if the setup time = 20 min.

Solution: The geometry of the part can be divided into two sections: (1) base and (2) walls. The cross-sectional area of the base $A_1 = 40^2 = 1600$ mm^2 and its thickness is given as 5 mm. The cross-sectional area of the walls $A_2 = 40^2 - 32^2 = 576$ mm^2 and its height = 52 − 5 = 47 mm. With a layer thickness = 0.10 mm, there will be 5.0/0.10 = 50 layers to build the base and 47/0.10 = 470 layers to fabricate the walls, a total of 470 + 50 = 520 layers.

The time per layer for the base

$$T_i = \frac{A}{vDE_p} + T_r = \frac{1600}{950(0.25)} + 21 = 6.737 + 21 = 27.737 \text{ s}$$

The time per layer for the walls

$$T_i = \frac{576}{950(0.25)} + 21 = 2.425 + 21 = 23.425 \text{ s}$$

Total build cycle time

$$T_c = 20(60) + 50(27.737) + 470(23.425) = \mathbf{13{,}597\ s = 226.6\ min = 3.777\ hr}$$

If a separate support structure must be constructed for the part, some RP machines require a second scan to accomplish this in each layer. For example, fused deposition modeling uses a second extruder if the support material is of a different type than the part material (e.g., lower melting point wax to support a plastic part). In this case, the time taken by the secondary work head must be added if the extruder heads operate sequentially, so Equation (32.1) becomes:

$$T_i = \frac{A_i}{vD} + \frac{A_{si}}{vD} + T_r \tag{32.3}$$

where A_{si} = support area in layer i, mm^2 (in^2). A separate term is used to allow for the possibility that the spot speed and diameter used for the support may be different than those used for the part itself. In some cases, the extruder heads can be operated simultaneously rather than sequentially, so the layering time depends

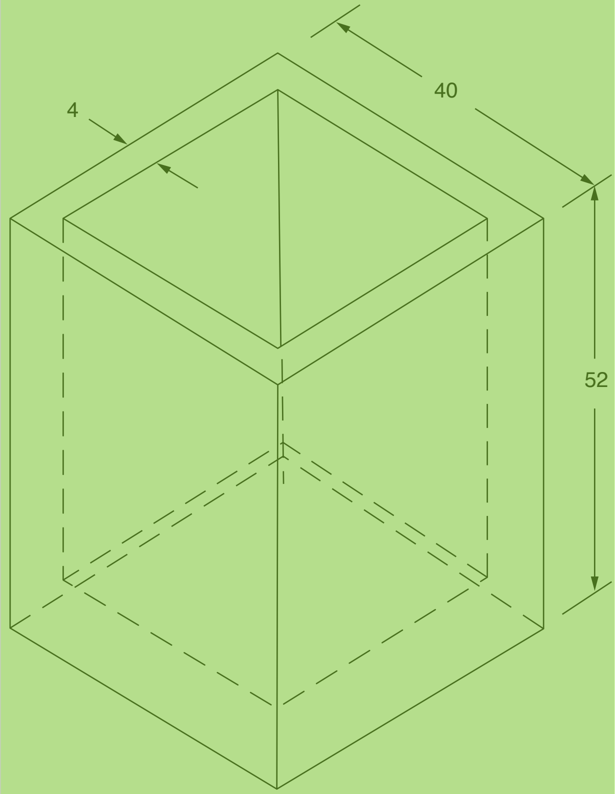

FIGURE 32.10 Sample part used in Example 32.1.

on whichever work head takes longer (usually the part work head because more material is deposited).

For processes that use a moving-line channel mode, the time to complete a layer is the time required for the moving line to sweep across the worktable plus repositioning and recoating time:

$$T_i = v_s L_s + T_r \tag{32.4}$$

where v_s = velocity of the moving line as it sweeps across the layer, mm/s (in/sec); and L_s = length of the sweep, mm (in). These values of v_s and L_s should be the same for all layers.

Finally, for processes using the layer channel mode, the time to complete one layer is given by

$$T_i = T_{ex} + T_r \tag{32.5}$$

where T_{ex} = exposure time to form the layer, s (sec). This should be the same for all layers.

The task of determining A_i for each layer can be tedious for a part of even modest geometric complexity. In these cases, it may be easier to determine the total volume of the part and divide this volume by the number of layers to determine the average volume per layer. Then, dividing this average volume by the layer thickness provides the average area per layer. Summarizing, the average layer area is given by

$$\overline{A}_i = \frac{V}{n_l t} \tag{32.6}$$

where V = total volume of the part, mm³ (in³); n_l = number of layers; and t = layer thickness, mm (in). Time to complete the layer then becomes

$$T_i = \frac{\overline{A}_i}{vD} + T_r = \frac{V}{n_l t v D} + T_r \tag{32.7}$$

where $\overline{A}_i$ = average area per layer, mm² (in²), and the other terms are the same as in Equation (32.1). The total cycle time equation, Equation (32.2), can then be reduced to the following forms:

$$T_c = T_{su} + n_l T_i = T_{su} + \frac{V}{tvD} + n_l T_r \tag{32.8}$$

where the terms on the far right-hand side are obtained by combining Equations (32.6) and (32.7) and expanding the T_i term.

Cost Analysis The cost per piece C_{pc} fabricated by any of the additive manufacturing technologies is the sum of material, labor, and machine operating cost. The following terminology and units will be used to develop equations to compute cost per piece: C_m = material cost, \$/pc; C_L = labor cost, \$/hr; C_{eq} = equipment cost, \$/hr. The build cycle time T_c has already been defined in Equations (32.2) and (32.8), but units of hours will be used here for convenience; that is T_c = cycle time, hr/cycle. Owing to the automated operation of the AM machine, a utilization factor U_L should be applied to the labor rate during the build cycle. Finally, a post-processing time per piece T_{pp} is the time following the build cycle that is required for support removal (if supports have been added to the part), cleaning, and finishing. Combining these terms, the piece cost can be computed from the following equation:

$$C_{pc} = C_m + (C_L U_L + C_{eq})\, T_c + C_L\, T_{pp} \tag{32.9}$$

Equipment cost per hour can be based on the original installed cost of the equipment divided by the total number of hours of operation the machine is expected to be used during its life, as explained in Section 1.5.2 and Example 1.1.

Example 32.2 Cost per piece in additive manufacturing

The cost of the stereolithography machine in Example 32.1 = \$100,000 installed. It operates 5 days per week, 8 hours per day, 50 weeks per year, and is expected to last 4 years. Material cost for the photopolymer = \$120/liter. Assume that all of the photopolymer in the container that is not used for the part can be reused. Labor rate = \$24.00/hr, but labor will be used for only = 25% of the build cycle, mostly for setup. The post-processing time = 6.0 min/part. Using the cycle time of 3.777 hr from Example 32.1, determine the part cost.

Solution: The number of hours of operation per year H = 50(5)(8) = 2000 hr/yr. The hourly equipment cost is calculated as follows:

$$C_{eq} = \frac{100{,}000}{4(2000)} = \mathbf{\$12.50/hr}$$

Material cost = \$120/L (1 L = 1 dm^3 = 1(10^6) mm^3). The part in Example 32.1 has a volume composed of the square base where $V_1 = 5(1600) = 8000$ mm^3 plus the walls, where $V_2 = 47(576) = 27{,}072$ mm^3. Total volume = 35,072 mm^3.

$C_m = (\$120\,(10^{-6})/\text{mm}^3)(35{,}072\text{ mm}^3) = \$4.21/\text{pc}$

Cost per piece $C_{pc} = 4.21 + (24.00(0.25) + 12.50)(3.777) + 24.00(6/60) =$ **\$76.48/pc**

In many additive manufacturing applications used for production, more than one part is made in the build cycle. Let n_b denote the batch size (number of parts built during the production cycle). Equation (32.9) can be amended as follows to account for batch size:

$$C_{pc} = C_m + \frac{(C_L U_L + C_{eq})T_c}{n_b} + C_L T_{pp} \tag{32.10}$$

32.4 Additive Manufacturing Applications

Applications of additive manufacturing can be classified into four categories: (1) design, (2) engineering analysis and planning, (3) tooling, and (4) parts production. These applications are discussed in the following paragraphs. The chapter concludes with a brief discussion of the problems encountered in additive manufacturing.

Design This was the initial application area for rapid prototyping systems. Designers are able to confirm their design by building a real physical model in minimum time using rapid prototyping. The features and functions of the part can be communicated to others more easily using a physical model than by a paper drawing or displaying it on a CAD system monitor. Design benefits attributed to rapid prototyping include [2]: (1) reduced lead times to produce prototype components, (2) improved ability to visualize the part geometry because of its physical existence, (3) earlier detection and reduction of design errors, and (4) increased capability to compute mass properties of components and assemblies.

Engineering Analysis and Planning The existence of an RP-fabricated part allows for certain types of engineering analysis and planning activities to be accomplished that would be more difficult without the physical entity. Some of the possibilities are (1) comparison of different shapes and styles to optimize aesthetic appeal of the part; (2) analysis of fluid flow through different orifice designs in valves fabricated by RP; (3) wind tunnel testing of different streamline shapes using physical models created by RP; (4) stress analysis of a physical model; (5) fabrication of preproduction parts as an aid in process planning and tool design; and (6) combining medical imaging technologies, such as magnetic resonance imaging, with RP to create models for doctors in planning surgical procedures or fabricating prostheses or implants.

Tooling When AM is adopted to fabricate production tooling, the term ***rapid tool making*** (RTM) is often used. RTM applications divide into two approaches [5]: ***indirect*** RTM method, in which a pattern is created by RP and the pattern is used to fabricate the tool, and ***direct*** RTM method, in which RP is used to make the tool itself. Examples of indirect RTM include the following [7], [12]: (1) use of an RP-fabricated part as the master in making a silicon rubber mold that is subsequently used as a production mold; (2) RP patterns to make the sand molds in sand casting (Section 11.1); (3) fabrication of patterns of low-melting point materials (e.g., wax) in limited quantities for investment casting (Section 11.2.4); and (4) making electrodes for EDM (Section 25.3.1).

Examples of direct RTM include [5], [7], [12]: (1) RP-fabricated mold cavity inserts that can be sprayed with metal to produce injection molds for a limited quantity of production plastic parts (Section 13.6) and (2) 3-D printing to create a die geometry in metallic powders followed by sintering and infiltration to complete the fabrication of the die.

Parts Production Additive manufacturing is increasingly being used to produce parts and products, and the term ***direct digital manufacturing*** is sometimes used for these applications. Parts production examples include [4], [12]: (1) plastic parts in small batch sizes that cannot be economically produced by injection molding because of high mold cost; (2) parts with intricate and/or complex geometries, especially internal geometric features, that cannot be made by conventional processes without assembly; (3) spare parts in circumstances where it is more feasible to fabricate a part when it is needed than to maintain an inventory; and (4) customized one-of-a-kind parts that must be made to correct size for each individual application. Examples of customized parts are found in medical applications such as bone replacements, hearing aid shells that must be fitted to an individual's ear, dental aligners (clear dental braces that gradually correct a patient's bite), and custom soccer shoes for professional athletes.

As the preceding examples illustrate, direct digital manufacturing is not a substitute for mass production. Instead, it is appropriate for low-volume production and mass customization, in which products are made in large numbers but each product is somehow unique. To generalize, the characteristics of production situations suited to additive manufacturing include the following [4]: (1) unique geometries, (2) complex shapes, (3) low quantities, even quantities of one, (4) quick turnaround, and (5) it is desirable to avoid the fabrication of special hard tooling. The requirement is that a CAD model of the item must be available.

Problems with Additive Manufacturing The principal problems with current AM processes include (1) part accuracy, (2) limited variety of materials, and (3) mechanical performance of the fabricated parts.

Several sources of error limit part accuracy in AM systems: (1) mathematical, (2) process related, or (3) material related [19]. Mathematical errors include approximations of part surfaces used in RP data preparation and differences between the slicing thicknesses and actual layer thicknesses in the physical part. The latter differences result in z-axis dimensional errors. An inherent limitation in the physical part is the steps between layers, especially as layer thickness is increased, resulting in a staircase appearance for sloping part surfaces. Process-related errors sometimes result from the particular part building technology used in the AM system. These errors degrade the shape of each layer as well as the registration between adjacent layers. Process errors can also affect the z-axis dimension. Finally, material-related errors include shrinkage and distortion. An allowance for shrinkage can be made by enlarging the CAD model of the part based on previous experience with the process and materials.

Current rapid prototyping systems are limited in the variety of materials they can process. For example, stereolithography is limited to photosensitive polymers. In general, the materials used in AM systems are not as strong as the production part materials that will be used in the actual product. This limits the mechanical performance of the prototypes and the amount of realistic testing that can be done to verify the design during product development.