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## 3.1 Introduction

Every product development process involving an additive manufacturing machine requires the operator to go through a set sequence of tasks. Easy-to-use “personal” 3D printing machines emphasize the simplicity of this task sequence. These desktop-sized machines are characterized by their low cost, simplicity of use, and ability to be placed in a home or office environment. The larger and more “industrial” AM machines are more capable of being tuned to suit different user requirements and therefore require more expertise to operate, but with a wider variety of possible results and effects that may be put to good use by an experienced operator. Such machines also usually require more careful installation in industrial environments.

This chapter will take the reader through the different stages of the process that were described in Chap. 1. Where possible, the different steps in the process will be described with reference to different processes and machines. The objective is to allow the reader to understand how these machines may differ and also to see how each task works and how it may be exploited to the benefit of higher quality results. As mentioned before, we will refer to eight key steps in the process sequence:

- Conceptualization and CAD
- Conversion to STL/AMF
- Transfer and manipulation of STL/AMF file on AM machine
- Machine setup
- Build
- Part removal and cleanup
- Post-processing of part
- Application

There are other ways to breakdown this process flow, depending on your perspective and equipment familiarity. For example, if you are a designer, you

may see more stages in the early product design aspects. Model makers may see more steps in the post-build part of the process. Different AM technologies handle this process sequence differently, so this chapter will also discuss how choice of machine affects the generic process.

The use of AM in place of conventional manufacturing processes, such as machining and injection molding, enables designers to ignore some of the constraints of conventional manufacturing. However, conventional manufacturing will remain core to how many products are manufactured. Thus, we must also understand how conventional technologies, such as machining, integrate with AM. This may be particularly relevant to the increasingly popular metal AM processes. Thus, we will discuss how to deal with metal systems in detail.

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## **3.2 The Eight Steps in Additive Manufacture**

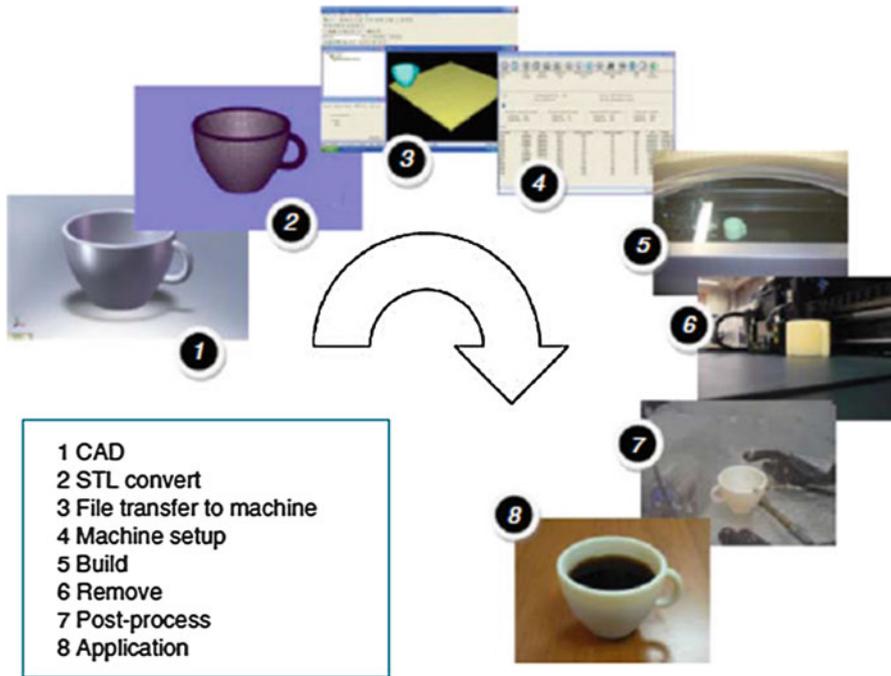
The above-mentioned sequence of steps is generally appropriate to all AM technologies. There will be some variations dependent on which technology is being used and also on the design of the particular part. Some steps can be quite involved for some machines but may be trivial for others.

### **3.2.1 Step 1: Conceptualization and CAD**

The first step in any product development process is to come up with an idea for how the product will look and function. Conceptualization can take many forms, from textual and narrative descriptions to sketches and representative models. If AM is to be used, the product description must be in a digital form that allows a physical model to be made. It may be that AM technology will be used to prototype and not build the final product, but in either case, there are many stages in a product development process where digital models are required.

AM technology would not exist if it were not for 3D CAD. Only after we gained the ability to represent solid objects in computers were we able to develop technology to physically reproduce such objects. Initially, this was the principle surrounding CNC machining technology in general. AM can thus be described as a direct or streamlined Computer Aided Design to Computer Aided Manufacturing (CAD/CAM) process. Unlike most other CAD/CAM technologies, there is little or no intervention between the design and manufacturing stages for AM.

The generic AM process must therefore start with 3D CAD information, as shown in Fig. 3.1. There may be a variety of ways for how the 3D source data can be created. This model description could be generated by a design expert via a user-interface, by software as part of an automated optimization algorithm, by 3D scanning of an existing physical part, or some combination of all of these. Most 3D CAD systems are solid modeling systems with surface modeling components; solid models are often constructed by combining surfaces together or by adding thickness to a surface. In the past, 3D CAD modeling software had difficulty



**Fig. 3.1** The eight stages of the AM process

creating fully enclosed solid models, and often models would appear to the casual observer to be enclosed but in fact were not mathematically closed. Such models could result in unpredictable output from AM machines, with different AM technologies treating gaps in different ways.

Most modern solid modeling CAD tools can now create files without gaps (e.g., “water tight”), resulting in geometrically unambiguous representations of a part. Most CAD packages treat surfaces as construction tools that are used to act on solid models, and this has the effect of maintaining the integrity of the solid data. Provided it can fit inside the machine, typically any CAD model can be made using AM technology without too many difficulties. However, there still remain some older or poorly developed 3D CAD software that may result in solids that are not fully enclosed and produce unreliable AM output. Problems of this manner are normally detected once the CAD model has been converted into the STL format for building using AM technology.

### 3.2.2 Step 2: Conversion to STL/AMF

Nearly every AM technology uses the STL file format. The term STL was derived from STereoLithograhy, which was the first commercial AM technology from 3D

Systems in the 1990s. Considered a de facto standard, STL is a simple way of describing a CAD model in terms of its geometry alone. It works by removing any construction data, modeling history, etc., and approximating the surfaces of the model with a series of triangular facets. The minimum size of these triangles can be set within most CAD software and the objective is to ensure the models created do not show any obvious triangles on the surface. The triangle size is in fact calculated in terms of the minimum distance between the plane represented by the triangle and the surface it is supposed to represent. In other words, a basic rule of thumb is to ensure that the minimum triangle offset is smaller than the resolution of the AM machine. The process of converting to STL is automatic within most CAD systems, but there is a possibility of errors occurring during this phase. There have therefore been a number of software tools developed to detect such errors and to rectify them if possible.

STL files are an unordered collection of triangle vertices and surface normal vectors. As such, an STL file has no units, color, material, or other feature information. These limitations of an STL file have led to the recent adoption of a new “AMF” file format. This format is now an international ASTM/ISO standard format which extends the STL format to include dimensions, color, material, and many other useful features. As of the writing of this book, several major CAD companies and AM hardware vendors had publically announced that they will be supporting AMF in their next generation software. Thus, although the term STL is used throughout the remainder of this textbook, the AMF file could be simply substituted wherever STL appears, as the AMF format has all of the benefits of the STL file format with many fewer limitations.

STL file repair software, like the MAGICS software from the Belgian company Materialise [1], is used when there are problems with the STL file that may prevent the part from being built correctly. With complex geometries, it may be difficult for a human to detect such problems when inspecting the CAD or the subsequently generated STL data. If the errors are small then they may even go unnoticed until after the part has been built. Such software may therefore be applied as a checking stage to ensure that there are no problems with the STL file data before the build is performed.

Since STL is essentially a surface description, the corresponding triangles in the files must be pointing in the correct direction; in other words, the surface normal vector associated with the triangle must indicate which side of the triangle is outside vs. inside the part. The cross-section that corresponds to the part layers of a region near an inverted normal vector may therefore be the inversion of what is desired. Additionally, complex and highly discontinuous geometry may result in triangle vertices that do not align correctly. This may result in gaps in the surface. Various AM technologies may react to these problems in different ways. Some machines may process the STL data in such a way that the gaps are bridged. This bridge may not represent the desired surface, however, and it may be possible that additional, unwanted material may be included in the part.

While most errors can be detected and rectified automatically, there may also be a requirement for manual intervention. Software should therefore highlight the

problem, indicating what is thought to be inverted triangles for instance. Since geometries can become very complex, it may be difficult for the software to establish whether the result is in fact an error or something that was part of the original design intent.

### **3.2.3 Step 3: Transfer to AM Machine and STL File Manipulation**

Once the STL file has been created and repaired, it can be sent directly to the target AM machine. Ideally, it should be possible to press a “print” button and the machine should build the part straight away. This is not usually the case however and there may be a number of actions required prior to building the part.

The first task would be to verify that the part is correct. AM system software normally has a visualization tool that allows the user to view and manipulate the part. The user may wish to reposition the part or even change the orientation to allow it to be built at a specific location within the machine. It is quite common to build more than one part in an AM machine at a time. This may be multiples of the same part (thus requiring a copy function) or completely different STL files. STL files can be linearly scaled quite easily. Some applications may require the AM part to be slightly larger or slightly smaller than the original to account for process shrinkage or coatings; and so scaling may be required prior to building. Applications may also require that the part be identified in some way and some software tools have been developed to add text and simple features to STL formatted data for this purpose. This would be done in the form of adding 3D embossed characters. More unusual cases may even require segmentation of STL files (e.g., for parts that may be too large) or even merging of multiple STL files. It should be noted that not all AM machines will have all the functions mentioned here, but numerous STL file manipulation software tools are available for purchase or, in some cases, for free download to perform these functions prior to sending the file to a machine.

### **3.2.4 Step 4: Machine Setup**

All AM machines will have at least some setup parameters that are specific to that machine or process. Some machines are only designed to run a few specific materials and give the user few options to vary layer thickness or other build parameters. These types of machines will have very few setup changes to make from build to build. Other machines are designed to run with a variety of materials and may also have some parameters that require optimization to suit the type of part that is to be built, or permit parts to be built quicker but with poorer resolution. Such machines can have numerous setup options available. It is common in the more complex cases to have default settings or save files from previously defined setups to help speed up the machine setup process and to prevent mistakes being made.

Normally, an incorrect setup procedure will still result in a part being built. The final quality of that part may, however, be unacceptable.

In addition to setting up machine software parameters, most machines must be physically prepared for a build. The operator must check to make sure sufficient build material is loaded into the machine to complete the build. For machines which use powder, the powder is often sifted and subsequently loaded and leveled in the machine as part of the setup operation. For processes which utilize a build plate, the plate must be inserted and leveled with respect to the machine axes. Some of these machine setup operations are automated as part of the start-up of a build, but for most machines these operations are done manually by a trained operator.

### **3.2.5 Step 5: Build**

Although benefitting from the assistance of computers, the first few stages of the AM process are semiautomated tasks that may require considerable manual control, interaction, and decision making. Once these steps are completed, the process switches to the computer-controlled building phase. This is where the previously mentioned layer-based manufacturing takes place. All AM machines will have a similar sequence of layering, including a height adjustable platform or deposition head, material deposition/spreading mechanisms, and layer cross-section formation. Some machines will combine the material deposition and layer formation simultaneously while others will separate them. As long as no errors are detected during the build, AM machines will repeat the layering process until the build is complete.

### **3.2.6 Step 6: Removal and Cleanup**

Ideally, the output from the AM machine should be ready for use with minimal manual intervention. While sometimes this may be the case, more often than not, parts will require a significant amount of post-processing before they are ready for use. In all cases, the part must be either separated from a build platform on which the part was produced or removed from excess build material surrounding the part. Some AM processes use additional material other than that used to make the part itself (secondary support materials). Later chapters describe how various AM processes need these support structures to help keep the part from collapsing or warping during the build process. At this stage, it is not necessary to understand exactly how support structures work, but it is necessary to know that they need to be dealt with. While some processes have been developed to produce easy-to-remove supports, there is often a significant amount of manual work required at this stage. For metal supports, a wire EDM machine, bandsaw, and/or milling equipment may be required to remove the part from the baseplate and the supports from the part. There is a degree of operator skill required in part removal, since mishandling of parts and poor technique can result in damage to the part. Different AM parts have

different cleanup requirements, but suffice it to say that all processes have some requirement at this stage. The cleanup stage may also be considered as the initial part of the post-processing stage.

### **3.2.7 Step 7: Post-Processing**

Post-processing refers to the (usually manual) stages of finishing the parts for application purposes. This may involve abrasive finishing, like polishing and sandpapering, or application of coatings. This stage in the process is very application specific. Some applications may only require a minimum of post-processing. Other applications may require very careful handling of the parts to maintain good precision and finish. Some post-processing may involve chemical or thermal treatment of the part to achieve final part properties. Different AM processes have different results in terms of accuracy, and thus machining to final dimensions may be required. Some processes produce relatively fragile components that may require the use of infiltration and/or surface coatings to strengthen the final part. As already stated, this is often a manually intensive task due to the complexity of most AM parts. However, some of the tasks can benefit from the use of power tools, CNC milling, and additional equipment, like polishing tubs or drying and baking ovens.

### **3.2.8 Step 8: Application**

Following post-processing, parts are ready for use. It should be noted that, although parts may be made from similar materials to those available from other manufacturing processes (like molding and casting), parts may not behave according to standard material specifications. Some AM processes inherently create parts with small voids trapped inside them, which could be the source for part failure under mechanical stress. In addition, some processes may cause the material to degrade during build or for materials not to bond, link, or crystallize in an optimum way. In almost every case, the properties are anisotropic (different properties in different direction). For most metal AM processes, rapid cooling results in different microstructures than those from conventional manufacturing. As a result, AM produced parts behave differently than parts made using a more conventional manufacturing approach. This behavior may be better or worse for a particular application, and thus a designer should be aware of these differences and take them into account during the design stage. AM materials and processes are improving rapidly, and thus designers must be aware of recent advancements in materials and processes to best determine how to use AM for their needs.

### 3.3 Variations from One AM Machine to Another

The above generic process steps can be applied to every commercial AM technology. As has been noted, different technologies may require more or less attention for a number of these stages. Here we discuss the implications of these variations, not only from process to process but also in some cases within a specific technology.

The nominal layer thickness for most machines is around 0.1 mm. However, it should be noted that this is just a rule of thumb. For example, the layer thickness for some material extrusion machines is 0.254 mm, whereas layer thicknesses between 0.05 and 0.1 mm are commonly used for vat photopolymerization processes, and small intricate parts made for investment casting using material jetting technology may have layer thicknesses of 0.01 mm. Many technologies have the capacity to vary the layer thickness. The reasoning is that thicker layer parts are quicker to build but are less precise. This may not be a problem for some applications where it may be more important to make the parts as quickly as possible.

Fine detail in a design may cause problems with some AM technologies, such as wall thickness, particularly if there is no choice but to build the part vertically. This is because even though positioning within the machine may be very precise, there is a finite dimension to the droplet size, laser diameter, or extrusion head that essentially defines the finest detail or thinnest wall that can be fabricated.

There are other factors that may not only affect the choice of process but also influence some of the steps in the process chain. In particular, the use of different materials even within the same process may affect the time, resources, and skill required to carry out a stage. For example, the use of water soluble supports in material extrusion processes may require specialist equipment but will also provide better finish to parts with less hand finishing required than when using conventional supports. Alternatively, some polymers require special attention, like the use (or avoidance) of particular solvents or infiltration compounds. A number of processes benefit from application of sealants or even infiltration of liquid polymers. These materials must be compatible with the part material both chemically and mechanically. Post-processing that involves heat must include awareness of the heat resistance or melting temperature of the materials involved. Abrasive or machining-based processing must also require knowledge of the mechanical properties of the materials involved. If considerable finishing is required, it may also be necessary to include an allowance in the part geometry, perhaps by using scaling of the STL file or offsetting of the part's surfaces, so that the part does not become worn away too much.

Variations between AM technologies will become clarified further in the following chapters, but a general understanding can be achieved by considering whether the build material is processed as a powder, molten material, solid sheet, vat of liquid photopolymer, or ink-jet deposited photopolymer.

### 3.3.1 Photopolymer-Based Systems

It is quite easy to set up systems which utilize photopolymers as the build material. Photopolymer-based systems, however, require files to be created which represent the support structures. All liquid vat systems must use supports from essentially the same material as that used for the part. For material jetting systems it is possible to use a secondary support material from parallel ink-jet print heads so that the supports will come off easier. An advantage of photopolymer systems is that accuracy is generally very good, with thin layers and fine precision where required compared with other systems. Photopolymers have historically had poor material properties when compared with many other AM materials, however newer resins have been developed that offer improved temperature resistance, strength, and ductility. The main drawback of photopolymer materials is that degradation can occur quite rapidly if UV protective coatings are not applied.

### 3.3.2 Powder-Based Systems

There is no need to use supports for powder systems which deposit a bed of powder layer-by-layer (with the exception of supports for metal systems, as addressed below). Thus, powder bed-based systems are among the easiest to set up for a simple build. Parts made using binder jetting into a powder bed can be colored by using colored binder material. If color is used then coding the file may take a longer time, as standard STL data does not include color. There are, however, other file formats based around VRML that allow colored geometries to be built, in addition to AMF. Powder bed fusion processes have a significant amount of unused powder in every build that has been subjected to some level of thermal history. This thermal history may cause changes in the powder. Thus, a well-designed recycling strategy based upon one of several proven methods can help ensure that the material being used is within appropriate limits to guarantee good builds [2].

It is also important to understand the way powders behave inside a machine. For example, some machines use powder feed chambers at either side of the build platform. The powder at the top of these chambers is likely to be less dense than the powder at the bottom, which will have been compressed under the weight of the powder on top. This in turn may affect the amount of material deposited at each layer and density of the final part built in the machine. For very tall builds, this may be a particular problem that can be solved by carefully compacting the powder in the feed chambers before starting the machine and also by adjusting temperatures and powder feed settings during the build.

### 3.3.3 Molten Material Systems

Systems which melt and deposit material in a molten state require support structures. For droplet-based systems like with the Thermojet process these

supports are automatically generated; but with material extrusion processes or directed energy deposition systems supports can either be generated automatically or the user can use some flexibility to change how supports are made. With water soluble supports it is not too important where the supports go, but with breakaway support systems made from the same material as the build material, it is worthwhile to check where the supports go, as surface damage to the part will occur to some extent where these supports were attached before breaking them away. Also, fill patterns for material extrusion may require some attention, based upon the design intent. Parts can be easily made using default settings, but there may be some benefit in changing aspects of the build sequence if a part or region of a part requires specific characteristics. For example, there are typically small voids in FDM parts that can be minimized by increasing the amount of material extruded in a particular region. This will minimize voids, but at the expenses of part accuracy. Although wax parts made using material jetting are good for reproducing fine features, they are difficult to handle because of their low strength and brittleness. ABS parts made using material extrusion, on the other hand, are among the strongest AM polymer parts available, but when they are desired as a functional end-use part, this may mean they need substantial finishing compared with other processes as they exhibit lower accuracy than some other AM technologies.

### **3.3.4 Solid Sheets**

With sheet lamination methods where the sheets are first placed and then cut, there is no need for supports. Instead, there is a need to process the waste material in such a way that it can be removed from the part. This is generally a straightforward automated process but there may be a need for close attention to fine detail within a part. Cleaning up the parts can be the most laborious process and there is a general need to know exactly what the final part is supposed to look like so that damage is not caused to the part during the waste removal stage. The paper-based systems experienced problems with handling should they not be carefully and comprehensively finished using sealants and coatings. For polymer sheet lamination, the parts are typically not as sensitive to damage. For metal sheet lamination processes, typically the sheets are cut first and then stacked to form the 3D shape, and thus support removal becomes unnecessary.

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## **3.4 Metal Systems**

As previously mentioned, operation of metal-based AM systems is conceptually similar to polymer systems. However, the following points are worth considering.

### **3.4.1 The Use of Substrates**

Most metal systems make use of a base platform or substrate onto which parts are built and from which they must be removed using machining, wire cutting, or a similar method. The need to attach the parts to a base platform is mainly because of the high-temperature gradients between the temporarily molten material and its surroundings, resulting in large residual stress. If the material was not rigidly attached to a solid platform then there would be a tendency for the part to warp as it cools, which means further layers of powder could not be spread evenly over top. Therefore, even though these processes may build within a powder bed, there is still a need for supports.

### **3.4.2 Energy Density**

The energy density required to melt metals is obviously much higher than for melting polymers. The high temperatures achieved during metal melting may require more stringent heat shielding, insulation, temperature control, and atmospheric control than for polymer systems.

### **3.4.3 Weight**

Metal powder systems may process lightweight titanium powders but they also process high-density tool steels. The powder handling technology must be capable of withstanding the mass of these materials. This means that power requirements for positioning and handling equipment must be quite substantial or gear ratios must be high (and corresponding travel speeds lower) to deal with these tasks.

### **3.4.4 Accuracy**

Metal powder systems are generally at least as accurate as corresponding polymer powder systems. Surface finish is characteristically grainy but part density and part accuracy are very good. Surface roughness is on the order of a few tens to a few hundreds of microns depending on the process, and can be likened in general appearance to precision casting technology. For metal parts, this is often not satisfactory and at least some shot-peening is required to smooth the surface. Key mating features on metal parts often require surface machining or grinding. The part density will be high (generally over 99 %), although some voids may still be seen.

### 3.4.5 Speed

Since there are heavy requirements on the amount of energy to melt the powder particles and to handle the powders within the machine, the build speed of metal systems is generally slower than a comparable polymer system. Laser powers are usually just a few 100 W (polymer systems start at around 50 W of laser power). This means that the laser scanning speed is lower than for polymer systems, to ensure enough energy is delivered to the powder.

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## 3.5 Maintenance of Equipment

While numerous stages in the AM process have been discussed, it is important to realize that many machines require careful maintenance. Some machines use sensitive laser or printer technology that must be carefully monitored and that should preferably not be used in a dirty or noisy (both electrical noise and mechanical vibration) environment. Similarly, many of the feed materials require careful handling and should be used in low humidity conditions. While machines are designed to operate unattended, it is important to include regular checks in the maintenance schedule. Many machine vendors recommend and provide test patterns that should be used periodically to confirm that the machines are operating within acceptable limits.

Laser-based systems are generally expensive because of the cost of the laser and scanner system. Furthermore, maintenance of a laser can be very expensive, particularly for lasers with limited lifetimes. Printheads are also components that have finite lifetimes for material jetting and binder jetting systems. The fine nozzle dimensions and the use of relatively high viscosity fluids mean they are prone to clogging and contamination effects. Replacement costs are, however, generally quite low.

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## 3.6 Materials Handling Issues

In addition to the machinery, AM materials often require careful handling. The raw materials used in some AM processes have limited shelf-life and must also be kept in conditions that prevent them from chemical reaction or degradation. Exposure to moisture and to excess light should be avoided. Most processes use materials that can be used for more than one build. However, it may be that this could degrade the material if used many times over and therefore a procedure for maintaining consistent material quality through recycling should also be observed.

While there are some health concerns with extended exposure to some photopolymer resins, most AM polymer raw materials are safe to handle. Powder materials may in general be medically inert, but excess amounts of powder can make the workplace slippery, contaminate mechanisms, and create a breathing hazard. In addition, reactive powders can be a fire hazard. These issues may

cause problems if machines are to be used in a design center environment rather than in a workshop. AM system vendors have spent considerable effort to simplify and facilitate material handling. Loading new materials is often a procedure that can be done offline or with minimal changeover time so that machines can run continuously. Software systems are often tuned to the materials so that they can recognize different materials and adjust build parameters accordingly.

Many materials are carefully tuned to work with a specific AM technology. There are often warranty issues surrounding the use of third party materials that users should be aware of. For example, some polymer laser sintering powders may have additives that prevent degradation due to oxidation since they are kept at elevated temperatures for long periods of time. Also, material extrusion filaments need a very tight diametric tolerance not normally available from conventional extruders. Since a material extrusion drive pushes the filament through the machine, variations in diameter may cause slippage. Furthermore, build parameters are designed around the standard materials used. Since there are huge numbers of material formulations, changing one material for another, even though they appear to be the same, may require careful build setup and process parameter optimization.

Some machines allow the user to recycle some or all of the material used in a machine but not consumed during the build of a prior part. This is particularly true with the powder-based systems. Also photopolymer resins can be reused. However, there may be artifacts and other contaminants in the recycled materials and it is important to carefully inspect, sift, or sieve the material before returning it to the machine. Many laser sintering builds have been spoiled, for example, by hairs that have come off a paintbrush used to clean the parts from a previous build.

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## **3.7 Design for AM**

Designers and operators should consider a number of build-related factors when considering the setup of an AM machine, including the following sections. This is a brief introduction, but more information can be found in [Chap. 17](#).

### **3.7.1 Part Orientation**

If a cylinder was built on its end, then it would consist of a series of circular layers built on top of each other. Although layer edges may not be precisely vertical for all AM processes, the result would normally be a very well-defined cylinder with a relatively smooth edge. The same cylinder built on its side will have distinct layer stair-step patterning on the sides. This will result in less accurate reproduction of the original CAD data with a poorer aesthetic appearance. Additionally, as the layering process for most AM machines takes additional time, a long cylinder built vertically will take more time to build than if it is laid horizontally. For material extrusion processes, however, the time to build a part is solely a factor of the total build

volume (including supports) and thus a cylinder should always be built vertically if possible.

Orientation of the part within the machine can affect part accuracy. Since many parts will have complex features along multiple axes, there may not be an ideal orientation for a particular part. Furthermore, it may be more important to maintain the geometry of some features when compared with others, so correct orientation may be a judgment call. This judgment may also be in contrast with other factors like the time it takes to build a part (e.g., taller builds take longer than shorter ones so high aspect ratio parts may be better built lying down), whether a certain orientation will generate more supports, or whether certain surfaces should be built face-up to ensure good surface finish in areas that are not in contact with support structures.

In general upward-facing features in AM have the best quality. The reason for this depends upon the process. For instance, upward-facing features are not in contact with the supports required for many processes. For powder beds, the upward-facing features are smooth since they solidify against air, whereas downward-facing and sideways-facing features solidify against powder and thus have a powdery texture. For extrusion processes, upward-facing surfaces are smoothed by the extrusion tip. Thus, this upward-facing feature quality rule is one of the few rules-of-thumb that are generically applicable to every AM process.

### 3.7.2 Removal of Supports

For those technologies that require supports, it is a good idea to try and minimize the amount. Wherever the supports meet the part there will be small marks and reducing the amount of supports would reduce the amount of part cleanup and post-process finishing. However, as mentioned above, some surfaces may not be as important as others and so positioning of the part must be weighed against the relative importance of an affected surface. In addition, removal of too many supports may mean that the part becomes detached from the baseplate and will move around during subsequent layering. If distortion causes a part to extend in the z direction enough that it hits the layering mechanism (such as a powder-spreading blade) then the build will fail.

Parts that require supports may also require planning for their removal. Supports may be located in difficult-to-reach regions within the part. For example, a hollow cylinder with end caps built vertically will require supports for the top surface. However, if there is no access hole then these supports cannot be removed. Inclusion of access holes (which could be plugged later) is a possible solution to this, as may be breaking up the part so the supports can be removed before reassembly. Similarly, parts made using vat photopolymerization processes may require drain holes for any trapped liquid resin.

### 3.7.3 Hollowing Out Parts

Parts that have thick walls may be designed to include hollow features if this does not reduce the part's functionality. The main benefits of doing this are the reduced build time, the reduced cost from the use of less material, and the reduced mass in the final component. As mentioned previously, some liquid-based resin systems would require drain holes to remove excess resin from inside the part, and the same is true for powder. A honeycomb- or truss-like internal structure can assist in providing support and strength within a part, while reducing its overall mass and volume. All of these approaches must be balanced against the additional time that it would take to design such a part. However, there are software systems that would allow this to be done automatically for certain types of parts.

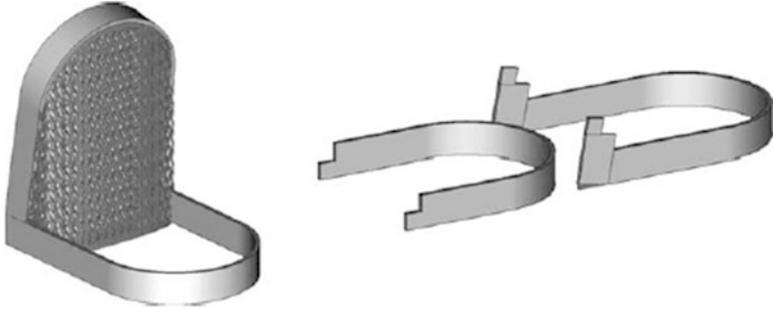
### 3.7.4 Inclusion of Undercuts and Other Manufacturing Constraining Features

AM models can be used at various stages of the product development process. When evaluating initial designs, focus may be on the aesthetics or ultimate functionality of the part. Consideration of how to include manufacturing-related features would have lower priority at this stage. Conventional manufacturing would require considerable planning to ensure that a part is fabricated correctly. Undercuts, draft angles, holes, pockets, etc. must be created in a specific order when using multiple-stage conventional processes. While this can be ignored when designing the part for AM, it is important not to forget them if AM is being used just as a prototype process. AM can be used in the design process to help determine where and what type of rib, boss, and other strengthening approaches should be used on the final part. If the final part is to be injection molded, the AM part can be used to determine the best location for the parting lines in the mold.

### 3.7.5 Interlocking Features

AM machines have a finite build volume and large parts may not be capable of being built inside them. A solution may be to break the design up into segments that can fit into the machine and manually assemble them together later. The designer must therefore consider the best way to break up the parts. The regions where the breaks are made can be designed in such a way as to facilitate reassembly. Techniques can include incorporation of interlocking features and maximizing surface area so that adhesives can be most effective. Such regions should also be in easy-to-reach but difficult-to-observe locations.

This approach of breaking parts up may be helpful even when they can still fit inside the machine. Consider the design shown in Fig. 3.2. If it was built as a single part, it would take a long time and may require a significant amount of supports (as shown in the left-hand figure). If the part were built as two separate pieces the



**Fig. 3.2** The build on the *left* (shown with support materials within the arch) can be broken into the two parts on the *right*, which may be stronger and can be glued together later. Note the reduction in the amount of supports and the reduced build height

resulting height would be significantly reduced and there would be few supports. The part could be glued together later. This glued region may be slightly weakened, but the individual segments may be stronger. Since the example has a thin wall section, the top of the upright band shown in the left side of the figure will exhibit stair-stepping and may also be weaker than the rest of the part, whereas the part build lying down would typically be stronger. For the bonded region, it is possible to include large overlapping regions that will enable more effective bonding.

### 3.7.6 Reduction of Part Count in an Assembly

There are numerous sections in this book that discuss the use of AM for direct manufacture of parts for end-use applications. The AM process is therefore toward the end of the product development process and the design does not need to consider alternative manufacturing processes. This in turn means that if part assembly can be simplified using AM, then this should be done. For example, it is possible to build fully assembled hinge structures by providing clearance around the moving features. In addition, complex assemblies made up of multiple injection molded parts, for instance, could be built as a single component. Thus, when producing components with AM, designers should always look for ways to consolidate multiple parts into a single part and to include additional part complexity where it can improve system performance. Several of the parts in Fig. 1.4 provide good examples of these concepts.

### 3.7.7 Identification Markings/Numbers

Although AM parts are often unique, it may be difficult for a company to keep track of them when they are possibly building hundreds of parts per week. It is a straightforward process to include identifying features on the parts. This can be

done when designing the CAD model but that may not be possible since the models may come from a third party. There are a number of software systems that provide tools for labeling parts by embossing alphanumeric characters onto them as 3D models. In addition, some service providers build all the parts ordered by a particular customer (or small parts which might otherwise get lost) within a mesh box so that they are easy to find and identify during part cleanup.

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## **3.8 Application Areas That Don't Involve Conventional CAD Modeling**

Additive manufacturing technology opens up opportunities for many applications that do not take the standard product development route. The capability of integrating AM with customizing data or data from unusual sources makes for rapid response and an economical solution. The following sections are examples where nonstandard approaches are applicable.

### **3.8.1 Medical Modeling**

AM is increasingly used to make parts based on an individual person's medical data. Such data are based on 3D scanning obtained from systems like Computerized Tomography (CT), Magnetic Resonance Imaging (MRI), 3D ultrasound, etc. These datasets often need considerable processing to extract the relevant sections before it can be built as a model or further incorporated into a product design. There are a few software systems that can process medical data in a suitable way, and a range of applications have emerged. For example, Materialise [1] developed software used in the production of hearing aids. AM technology helps in customizing these hearing aids from data that are collected from the ear canals of individual patients.

### **3.8.2 Reverse Engineering Data**

Medical data from patients is just one application that benefits from being able to collect and process complex surface information. For nonmedical data collection, the more common approach is to use laser scanning technology. Such technology has the ability to faithfully collect surface data from many types of surfaces that are difficult to model because they cannot be easily defined geometrically. Similar to medical data, although the models can just be reproduced within the AM machine (like a kind of 3D copy machine), the typical intent is to merge this data into product design. Interestingly, laser scanners for reverse engineering and inspection run the gamut from very expensive, very high-quality systems (e.g., from Leica and Steinbichler) to mid-range systems (from Faro and Creaform) to Microsoft Kinect™ controllers.

### 3.8.3 Architectural Modeling

Architectural models are usually created to emphasize certain features within a building design and so designs are modified to show textures, colors, and shapes that may not be exact reproductions of the final design. Therefore, architectural packages may require features that are tuned to the AM technology.

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## 3.9 Further Discussion

AM technologies are beginning to move beyond a common set of basic process steps. In the future we will likely see more processes using variations of the conventional AM approach, and combinations of AM with conventional manufacturing operations. Some technologies are being developed to process regions rather than layers of a part. As a result, more intelligent and complex software systems will be required to effectively deal with segmentation.

We can expect processes to become more complex within a single machine. We already see numerous additive processes combined with subtractive elements. As technology develops further, we may see commercialization of hybrid technologies that include additive, subtractive, and even robotic handling phases in a complex coordinated and controlled fashion. This will require much more attention to software descriptions, but may also lead to highly optimized parts with multiple functionality and vastly improved quality with very little manual intervention during the actual build process.

Another trend we are likely to see is the development of customized AM systems. Presently, AM machines are designed to produce as wide a variety of possible part geometries with as wide a range of materials as possible. Reduction of these variables may result in machines that are designed only to build a subset of parts or materials very efficiently or inexpensively. This has already started with the proliferation of “personal” versus “industrial” material extrusion systems. In addition, many machines are being targeted for the dental or hearing aid markets, and system manufacturers have redesigned their basic machine architectures and/or software tools to enable rapid setup, building, and post-processing of patient-specific small parts.

Software is increasingly being optimized specifically for AM processing. Special software has been designed to increase the efficiency of hearing aid design and manufacture. There is also special software designed to convert the designs of World of Warcraft models into “FigurePrints” (see Fig. 3.3) as well as specially designed post-processing techniques [3]. As Direct Digital Manufacturing becomes more common, we will see the need to develop standardized software processes based around AM, so that we can better control, track, regulate, and predict the manufacturing process.

**Fig. 3.3** FigurePrints model, post-processed for output to an AM machine



### 3.9.1 Exercises

1. Investigate some of the web sites associated with different AM technologies. Find out information on how to handle the processes and resulting parts according to the eight stages mentioned in this chapter. What are four different tasks that you would need to carry out using a vat photopolymerization process that you wouldn't have to do using a binder jetting technology and vice versa?
2. Explain why surface modeling software is not ideal for describing models that are to be made using AM, even though the STL file format is itself a surface approximation. What kind of problems may occur when using surface modeling only?
3. What is the VRML file format like? How is it more suitable for specifying color models to be built using Color ZCorp machines than the STL standard? How does it compare with the AMF format?
4. What extra considerations might you need to give when producing medical models using AM instead of conventionally engineered products?
5. Consider the FigurePrints part shown in Fig. 3.3, which is made using a color binder jetting process. What finishing methods would you use for this application?

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### References

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