Chapter 3
Generalized Additive Manufacturing Process Chain

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 "desktop" or "3D printing" machines emphasize the simplicity of this task sequence. These desktop machines are characterized by their low cost, simplicity of use, and ability to be placed in an office environment. For these machines each step is likely to have few options and require minimal effort. However, this also means that there are generally fewer choices, with perhaps a limited range of materials and other variables to experiment with. The larger and more versatile machines are more capable of being tuned to suit different user requirements and therefore are more difficult 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 workshop environments.

This chapter will take the reader through the different stages of the process that were described in much less detail 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
- Transfer and manipulation of STL file on AM machine
- Machine setup
- Build
- Part removal and cleanup
- Post-processing of part
- Application

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There may be other ways to look at this process that depend on your perspective and equipment you are familiar with. For example, if you are a designer, you may see more stages in the product design. Model makers may see more steps in the post-processing of parts. However, our objective is to focus on the AM technology and so we will investigate the stages defined above in more detail. Different AM technologies need to be handled differently with regards to this process sequence, so this chapter will also discuss how choice of machine affects the generic process. We will also discuss how AM in general might affect the way models are designed. This is particularly relevant to applications where the intent is to avoid conventional manufacture, like machining and injection molding, in the production process. We are only just beginning to realize how designers can benefit from AM technology by being able to ignore some of the constraints of conventional manufacturing. However, conventional manufacturing cannot be ignored completely since it is still the core to how most 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.

3.2 The Eight Steps in Additive Manufacture

This 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 could be quite involved for some machines but may be trivial for others. While most of the initial discussion below is with respect to production of polymer parts, most steps can be generalized to metal systems as well.

3.2.1 Step 1: Conceptualization and CAD

The first step in any product development process is to come up with some idea as to 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 form that allows a physical model to be made. It may be that AM technology will not be used to realize the final product, but for complex products there are likely to be many stages in the development process where models can be used. For these purposes it is therefore important that the model description be entered into a computer.

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 as to how the 3D source data can be created. This model description could be generated by a computer user, using a user-interface, or via reverse engineering technologies. Most 3D CAD systems are solid modeling systems with some surface modeling components. That is to say that solid models are sometimes constructed by combining surfaces together or by adding thickness to a surface. In the past, 3D CAD modeling software had difficulty creating fully enclosed solid models, and often models would appear to the casual observer to be enclosed but in fact were not. Such models could result in unpredictable output from AM machines, with different AM technologies treating gaps in different ways.

Today, CAD software has developed to the extent that there are very few problems with surface discontinuities, with extensive checking and correction software built in to most systems. 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 remains some older or poorly developed 3D CAD software that may result in solids that are not fully enclosed and produce unreliable AM

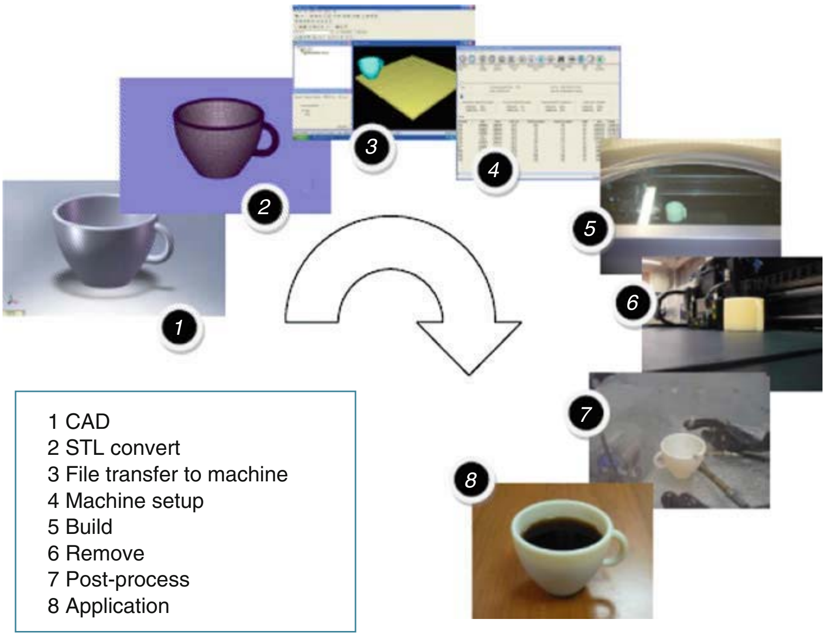

Fig. 3.1 The eight stages of the AM process

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*

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 file repair software, like the MAGICS software from the Belgian company Materialise [1], is used when there are problems with the file generated by the CAD system that may prevent the part from being built correctly. With complex geometries, it may be difficult 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, 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.

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 perhaps one or two different materials and with no variation in layer thickness or other build parameters. These types of machine 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 layer resolution, for example. 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.

3.2.5 Step 5: Build

Although benefitting from the assistance of computers, the first few stages of the AM process are semi-automated 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 layer control, using a height adjustable platform, material deposition, and layer cross-section formation. Some machines will combine the material deposition and layer formation simultaneously while others will separate them. All machines will repeat the process until either the build is complete or there is no source material remaining. In either case, the machine will alert the user to take action.

3.2.6 Step 6: Removal and Cleanup

Ideally, by this stage the output from the AM machine should be ready for use. While sometimes this may be the case, more often than not parts will still require a significant amount of manual finishing 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). This material will be used to aid the building process in some way. Later descriptions of the AM processes will discuss the need for these support structures to help keep the part from collapsing or warping during the building 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 still often a significant amount of manual work required at this stage. There is also a degree of manual skill required since mishandling of parts and poor technique in support removal can result in a low quality output. 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-process

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; taking advantage of the speed at which the parts are made. Other applications may require very careful handling of the parts to maintain good precision and finish. Different AM processes have different results in terms of accuracy and material properties. 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 primarily a manual task due to the complexity of most AM parts. However, some of the tasks can benefit from the use of power tools 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 or bubbles 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). This may result in parts that behave differently than if they were made using a more conventional manufacturing approach. However, AM materials and processes are improving all the time, and many applications do not require high performance from many of their components. The number of applications for the output from AM processes is therefore constantly increasing.

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 most FDM Dimension machines is 0.254 mm. Contrast that with standard layer thicknesses between 0.05 and 0.1 mm for SL technology. 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 FDM 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 had 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 these systems, although there is a need to generate support files. All liquid vat systems must use supports from essentially the same material as that used for the part. With droplet deposition it is possible to modify the support material as it comes out of the print head so that the supports will come away 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; but 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. Thus, powder bed-based systems are amongst the easiest to set up for a simple build. ZCorp parts created using binder printing into a powder bed are somewhat unique in AM in that parts can be colored by using colored binder material. If color is used then coding the file may take a long time, as standard STL data do not include color. There are, however, other file formats based around VRML that allow colored geometries to be built. Selective Laser Sintering (SLS) is a different powder bed process that requires attention to the material properties, particularly since these properties can change depending on how many times that material in the bed has been recycled. This means that it is important to check on the build periodically, watching the melting process to ensure the material is behaving as expected. A well-implemented 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 the powders behave inside the machine. For example, some SLS machines use two 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 extrusion processes like FDM supports can either be generated automatically or the user can use some flexibility, particularly for the higher end machines, 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 FDM may require some attention, based upon the design intent. Parts can be easily made using the default FDM 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 Thermojet parts are good for reproducing fine features, they are difficult to handle because of their low strength and brittleness. FDM parts, on the other hand, are amongst 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 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. The Solido process based upon bonding of polymer sheets does not seem to be quite so problematic.

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. If the material did not adhere to a solid platform then there would be a tendency for the part to warp as it cools, which means further layers of powder cannot be spread evenly. Therefore, even though these are mainly powder-based systems, there is still a need for supports.

3.4.2 Energy Density

The energy requirements for melting metals to over 1,000°C is obviously much higher than heating polymers to around 200°C. Heat shielding, insulation, temperature control, and atmospheric control are much more stringent than in the lower cost 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 in 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 is generally slower than a comparable sized polymer system. Laser powers are not excessively high, usually just a few hundred watts (polymer systems start at around 50 watts of laser power). This means that the laser scanning speed is quite low to ensure enough energy is delivered to the powder.

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 fragile 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. As indicated earlier, AM processes fall outside of many materials and process standards. However, 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 itself. Furthermore, maintenance of a laser can be very expensive since the expected lifetime can be as low as 4,000 operating hours for tube lasers and up to more than 15,000 h for solid state lasers. Printheads are also components that have finite lifetimes for the printer-based systems. The fine nozzle dimensions and the use of relatively high viscosity fluids mean they are quite prone to clogging and contamination effects. Replacement costs are, however, generally quite low.

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, etc. This may cause particular 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 now 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 since there is a potential danger to the equipment or reduction in part quality. For example, SLS powders may have additives that prevent degradation due to oxidation since they are kept at elevated temperatures for long periods of time. Also, FDM filaments are extruded to a very tight diametric tolerance not normally available from conventional extruders. Since the FDM material 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 are apparently the same, may still require careful build setup.

Some machines allow the user to recycle some or all of the material from a build that did not form the earlier part. This is particularly true with the powder-based systems. Also SL 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 SLS builds have been spoilt, for example, by hairs that have come off a paintbrush used to clean the parts from a previous build.

3.7 Design for AM

Designers and operators should consider a number of build-related factors when considering the set-up of an AM, including the following sections.

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 in all AM processes, the result would still normally be a very well defined cylinder with a relatively smooth edge. The same cylinder built on its side, so that the circular end is vertical, will have distinct layer patterning on the sides. This will result in less accurate reproduction of the original CAD data with a poorer esthetic appearance.

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.

3.7.2 Removal of Supports

For those technologies that require supports it is a good idea to try and minimize the amount. No matter which system you use, any down-facing surface will be marginally poorer in surface quality than surfaces that point upwards and to the outside. Supports exacerbate this situation. Wherever the supports meet the part there will be small marks and reducing the amount of supports would make the part more accurate and 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.

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, SL parts 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 doesn't impede the final functionality. The main benefits of doing this are the reduced time that may result during building of the part and the reduced cost from the use of less material. As mentioned previously, some liquid-based resin systems would require drain holes to remove excess resin from inside the part, which may not be an ideal solution. For these and other systems it may be that a honeycomb- or truss-like internal structure can assist in providing support within the part. All 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.

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 esthetics 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 processes. While this can be ignored when designing the part for additive processes, it is important not to forget them. Design at this stage may help in optimizing the parts since it would be possible to 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 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 still 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 require a significant amount of supports (as shown in the left-hand figure). If the part were built as two separate pieces the 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 one of the bands will exhibit more stair-stepping and may also be a little weaker than the rest of the part. For the bonded region, it is possible to include large overlapping regions that will enable more effective bonding.

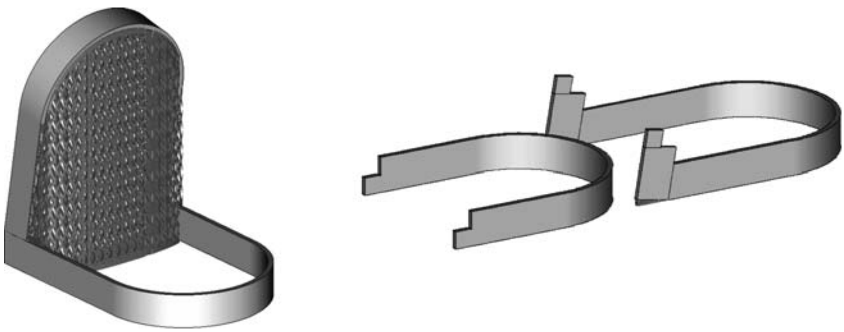

Fig. 3.2 The build on the *left* (shown with support materials within the arch) can be broken into the two builds on the *right*, which may be stronger and can be glued together later. Note the reduction in the amount of supports and the reduced build height

3.7.6 Reduction of Part Count in an Assembly

There are numerous sections in this book that discuss Direct Digital Manufacturing. This involves the direct manufacture of parts on AM machines for end use. The AM part 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 the part 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. What would conventionally be made up of a number of components in an assembly can possibly be designed as a single unit.

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.

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

There is an excellent opportunity to use AM in making models based on an individual person's medical data. The data can be incorporated into the system in a variety of different ways. Such data is based on 3D scanning obtained from systems like Computerized Tomography (CT), Magnetic Resonance Imaging (MRI), 3D ultrasound, etc. This data often needs considerable processing to extract the relevant sections before it can be built as a model or further incorporated into a product design. There are only a handful of software systems that can process the medical data in a suitable way, and a range of applications is starting to emerge. For example, Materialise [1] was involved in the development of software that is used in the production of hearing aids. AM technology helps in customizing these hearing aids from data that is 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 capacity to faithfully collect surface data from many types of surface that are difficult to model because they cannot be easily defined geometrically. Similar to the medical data, although the models can just be reproduced within the AM machine (like a kind of 3D fax machine), the general intention is to merge this data into products.

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.

3.9 Further Discussion

As indicated above, we are beginning to see the developments of AM technologies moving beyond a common set of basic process steps. In the future, for example, we will likely see more processes using variations of the conventional AM approach. Some technologies may move to thicker layers or to processing regions rather than layers, both of which have been successfully demonstrated. If so, then more intelligent and complex software systems will be required to effectively deal with segmentation. There are also processes that do not work well with the STL file format. Color and other forms of multiple material systems will become more common in the future. Other formats will be necessary so that part information can be described in a hierarchical fashion or volumetrically as well.

Furthermore, 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 additive 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 cheaply. This has already started with the different FDM systems manufactured by Stratasys, where the inexpensive Dimension machines are only capable of using one or two materials rather than the more versatile Fortus machines. Alternatively one might look to the proliferation of machines which are being targeted for the dental or hearing aid markets, where system manufacturers are starting to redesign 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, and regulate 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 SL that you wouldn't have to do using ZCorp 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?
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 ZCorp process. What finishing methods would you use for this application?

References

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3. Figureprints, 3DP models from World of Warcraft figures. www.figureprints.com