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

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
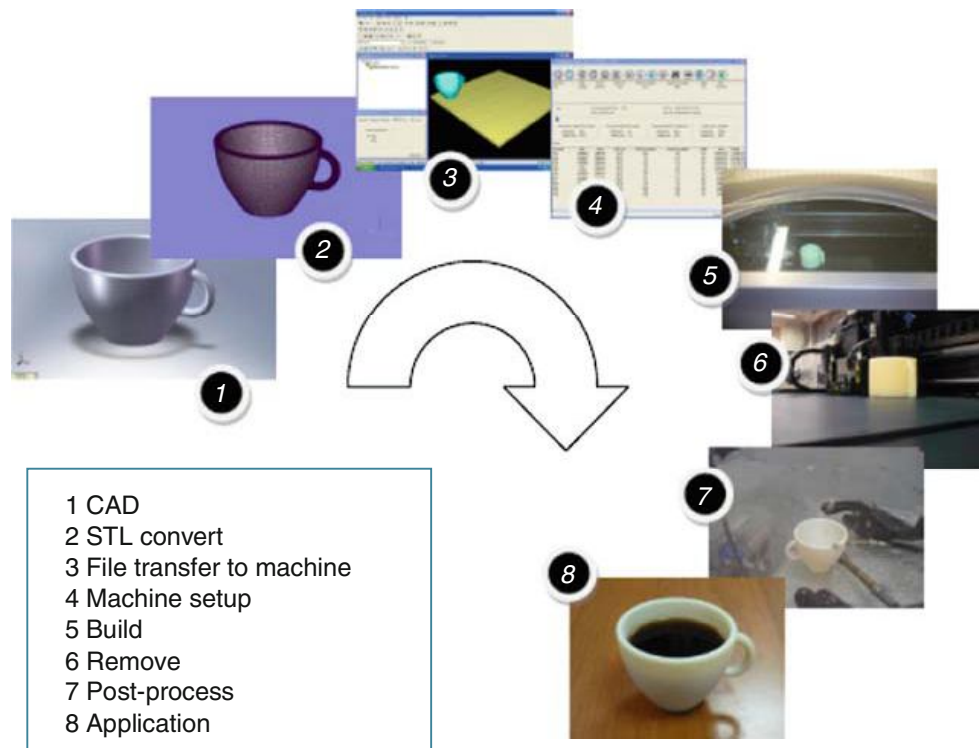

1 CAD
2 STL convert
3 File transfer to machine
4 Machine setup
5 Build
6 Remove
7 Post-process
8 Application

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,