

# Chapter 2

## Additive Manufacturing Process Chain

A series of steps goes into the process chain required to generate a useful physical part from the concept of the same part using additive manufacturing processes. Depending on the technology and, at times the machines and components, the process chain is mainly made up of six steps:

- Generation of CAD model of the design;
- Conversion of CAD model into AM machine acceptable format;
- CAD model preparation;
- Machine setup;
- Part removal;
- Post-processing.

These steps can be grouped or broken down and can look different from case to case, but overall the process chain from one technology remains similar to that of a different technology. The process chain is also constantly evolving and can change as the existing technologies develop and new technologies surface. In this text, the focus will be on the powder bed metal technology. Therefore, the process chain for this technology will be discussed in details, while other will be roughly mentioned.

### 2.1 Generation of Computer-Aided Design Model of Design

In any product design process the first step is to imagine and conceptualize the function and appearance of the product. This can take the form of textual descriptions, sketches, to 3-dimensional computer models. In terms of process chain, the first enabler of AM technologies is 3D digital Computer-Aided Design

(CAD) models where the conceptualized product exist in a “computer” space and the values of its geometry, material, and properties are stored in digital form and are readily retrievable.

In general the AM process chains start with 3D CAD modeling. The process of producing a 3D CAD model from an idea in the designer’s mind can take on many forms, but all requires CAD software programs. The details of these programs and the technology behind them is outside of the scope of this text, but these programs are a critical enabler of a designer’s ability to generate a 3D CAD model that can serve as the start of an AM process chain. There are a large number of CAD programs with different modeling principles, capabilities, accessibilities, and cost. Some examples includes Autodesk Inventor, Solidworks, Creo, NX, etc. The examples here are, by no means, representatives of CAD technologies, but intended to provide a few key words with which a search on topics on CAD can provide specific information a reader needs.

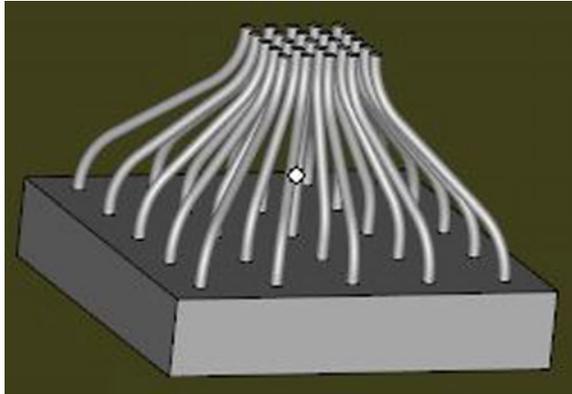
Once a 3D CAD model is produced, the steps in the AM process chain can take place. Though the process chain typically progresses in one direction that starts with CAD modeling and ends with a finished part or prototype, it is often an iterative process where changes to the CAD model and design are made to reflect feedback from each steps of the process chain. Specific to the metal powder bed technology, critical feedback can come from geometry and property an-isotropy on parts due to build orientation, distortion of part or features due to thermal history of build, issues in generating and removal of support structures, etc. Issues like these may rise in the AM process chain and may call for design changes and revisions. Similar to the topic of “design for manufacturability” in the conventional manufacturing space, design for additive manufacturing is critical and is developing in parallel with the technologies themselves. Chapter 5 is devoted to discussion of design for AM.

## **2.2 Conversion of CAD Model into AM Machine Acceptable Format**

Almost all AM technology available today uses the STereoLithography (STL) file format. Shown in Fig. 2.1 is an example part in its STL format. The STL format of a 3D CAD model captures all surfaces of the 3D model by means of stitching triangles of various sizes on its surfaces. The spatial locations of the vertices of each triangle and the vectors normal to each triangle, when combined, these features allow AM pre-process programs to determine the spatial locations of surfaces of the part in a build envelope, and on which side of the surface is the interior of the part.

Although the STL format has been consider the de facto standard, it has limitations intrinsic to the fact that only geometry information is stored in these files while all other information that a CAD model can contain is eliminated. Information such as unit, color, material, etc. can play critical role in the functionality of the built part is lost through the file translation process. As such it places

**Fig. 2.1** An example part in STL format



limitations on the functionality of the finished parts. The “AMF” format was developed specifically to address these issues and limitations, and is now the ASTM/ISO standard format. Beyond geometry information, it also contains dimensions, color, material, and additional information is also possible with this file format. Though currently the predominate format of file used by AM systems and supported by CAD modeling programs is still the STL format. An increasing number of CAD program companies, including several major programs, have included support of AMF file formats. Currently, actual use of the information stored in the AMF file is still limited due to the capabilities of current AM systems and the state of current technology development.

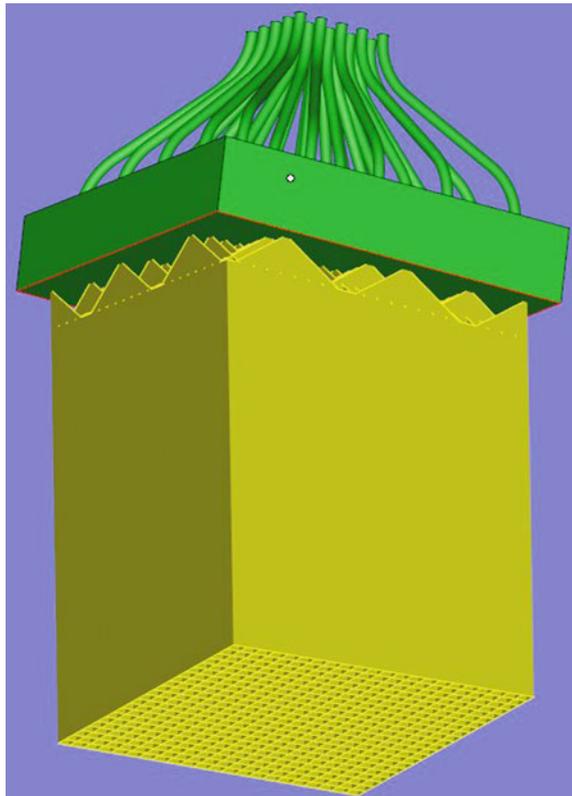
### 2.3 CAD Model Preparation

Once a correct STL file is available, a series of steps is required to generate the information an AM system needs to start the build process. The needed information varies, depending on the technology but in general these steps start with repairing any errors within the STL file. Typical errors can be gaps between surface triangle facets, inverted normal where the “wrong side” of a triangle facet is identified as the interior of the part. Once the errors have been repaired, a proper orientation of the 3D model with respect to the build platform/envelope is then decided. Following the orientation, the geometry, density, geometry of support structures are decided and generated in 3D model space and assigned to the part model. The process then progresses to slicing the 3D model defined by the STL as well the support structure into a given number of layers of a desired height each representing a slice of the part and support models. Within each slice the cross-sectional geometry is kept constant. Once 2D slices are obtained, a “unit” area representing the smallest material placement is then used, combined with a set of strategies, to fill the area within each

layer that is enclosed by the surface of the part and the support. For the SLA process, the unit area is related to the laser spot size and its intensity distribution as well as absorption of monomer, and the strategies of filling the enclosed area in one layer is the path in which the laser would raster the resin surface. At this point the surface data that are originally in the STL file has been processed and machine specific information to allow placement of the material unit into the desired location in a controlled manner to construct the physical model layer by layer (Fig. 2.2).

Specifically for metal powder bed processes, a STL file is first imported into a software that allows repairing and manipulating of the file, as well as the generation of support, and the slicing of the part and support models. The sliced data are then transferred into the AM system machine for build preparation and the start of the building process. There are a number of software programs that allow these tasks to be carried out, Magics, for example by Materialise is one such software program that is capable of integrating all CAD model preparation steps into one program and generating data files directly accepted by powder bed machine systems. In the sections below additional details of model preparation specific to the powder bed metal process is described.

**Fig. 2.2** Support structure generated on the model



### ***2.3.1 STL File Preparation***

The CAD model preparation starts with importing an STL, or other compatible file formats, into the pre-process software program (e.g., Magics). Once imported, the dimensions can be modified if needed. Once the model is in desired dimensions, a series of steps is carried out to correct possible errors in the model file. These errors can include missing triangles, inverted or double triangles, transverse triangles, open edges and contours, and shells. Each type of error can cause issues in the building process or result in incorrect parts and geometries. While some errors such as shells and double triangles are non-critical and can sometimes be tolerated, errors such as inverted triangles and open contours can cause critical issue in the building process and needs to be resolved during STL preparation.

### ***2.3.2 Support Generation***

For metal powder bed process, the primary function of the “support” structure is to extract heat from the model and to provide anchor surfaces and features to the build plate to avoid warpage due to thermal stresses during and after the build. It does not “support” the part against gravity that causes over hanging or angled features to fail to build.

Generation of support structures in powder bed processes can be accomplished in a few different ways. Also applied to any other AM processes, the first way is to generate the support structures during CAD modeling and design the support to be features of the geometry of the part. Alternatively, the support structures can be generated in the STL preprocess software program. This second approach provides much more flexibility in terms of being able to tailor the structures based on the detailed needs. For example, since the support structure is only used during the build process and is removed during post-process, the amount of material that goes into it needs to be minimized. However, since the primary function of the support is to conduct heat and provide mechanical anchor, a minimum amount of cross-sectional area in the support is needed for it to be functional. Optimization of the volume, geometry, location, and the part-support interface geometry, is important and part dependent. Therefore, careful design of support structure plays a critical role in the success of a build process. Figure 2.2 shows examples of support generated in CAD model space.

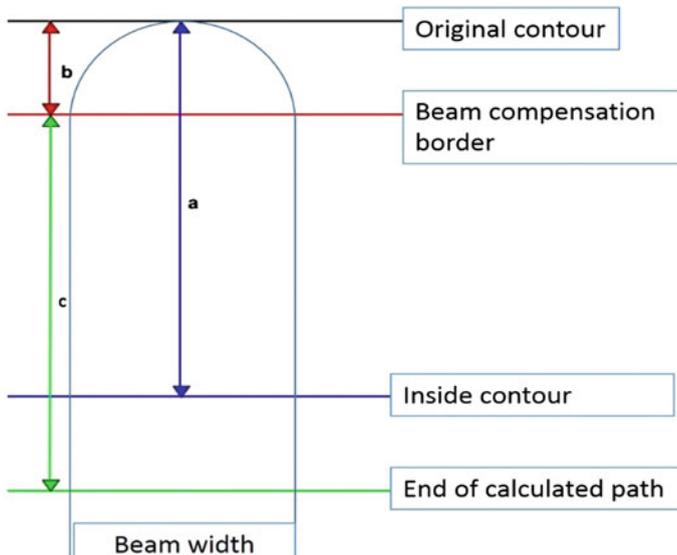
### ***2.3.3 Build File Preparation***

Once the CAD models of part and support are generated and prepared in the pre-process software program, a slicer program is used to divide the models into

layers in the build direction based on the desired layer thickness. For typical metal powder bed systems the layer thickness can be anywhere from 25 microns to close 100 microns. Typical thicknesses used are 25 microns for high resolution builds and 50–75 microns or higher for high-rate applications. Layer thickness is also correlated to the powder dimension and distribution. Ideally the layer thickness would be slightly larger than the mean diameter of powder to achieve high coupling of laser energy input into the absorption, heating and melting of powder, and re-melting of previous layer. At larger thicknesses, scattering of optical energy input may not be sufficient to allow uniform optical energy absorption and heating, resulting in partial melting.

Within each slice, the slicer software also determines the rastering path that the energy beam takes to fully melt the entire layer. How a meltpool created by an optical beam can move in an enclosed area to ensure every part of it is covered is analogous to how an end-milling tool does a pocket milling operation to create an enclosed 2D area with a depth on a surface. Figure 2.3 shows how the use of contour scan coupled with in-fill to fully cover an area. As seen in the illustration, an important factor is the beam diameter, which is captured by the Beam compensation parameter. This value is typically chosen such that sufficient over lapping of adjacent paths occurs and partial melting is avoided.

Other important parameters includes “islands” within each layer, and shifting of scan directions, offset of scan lines from layer to layer as build progresses. The use of islands is important in that the rapid heat generation and cooling in the build part as a result of absorbing a fast-moving optical energy input source ( $\sim 1000$  mm/s). Heat input into small “islands” of randomized locations within a layer allows the



**Fig. 2.3** Beam compensation to determine correct beam paths

heat to be evenly introduced spatially, and reduces the chance of deformation and failures caused by uneven warpage during a build. Changing of scan directions and offsetting scan lines from layer to layer allows for uniform distribution of scanline-wise thermal and microstructural anisotropy in the entire 3D space within a build part. It allows for the overall isotropy of material properties.

In addition to rastering strategy, critical parameters that determine energy input into the powder bed to achieve controlled melting are beam power (laser or electron beam), scan speed, and focus move (if the hardware of the systems allows). Overall, these parameters determine the amount of energy incident onto the powder bed per unit time, and directly relates to the heating, melting, and cooling of the material. Each factor, however, also plays a role in different characteristics of the build. High power at faster scan rate produces different thermal history as compared with lower power at slower scan rates, even if the total power input are the same. As a result of the differences in thermal history, the microstructures and properties of parts can differ. In addition, the advective flow of molten material in the meltpool can also have different behaviors when the meltpool travels at different rates, resulting in also differences in the solidification process.

Once the slice information is generated, it is transferred into the interface program that runs on AM systems. The interface program serves as the interface between information of the build and machine controls that carry out the actual build process.

## 2.4 Machine Setup

Following software preparation steps in the AM process chain, machine preparation is the next step before a build can start. Machine preparation can roughly be divided into two groups of tasks: machine hardware setup, and process control. Hardware setup entails cleaning of build chamber from previous build, loading of powder material, a routine check of all critical build settings and process controls such as gas pressure, flow rate, oxygen sensors, etc. Details of how each task in this group is carried out can vary from one system to another, but overall once the machine hardware setup is complete, the AM system is ready to accept the build files (slices generated from previous step) and start the build.

The tasks in the process control task group allow an AM system to accept and process the build files, start the build, interrupt the build at any given time if desired or required, and preparing the machine for finished part extraction, and unloading of material. This first task is usually importing and positioning of build parts in the area defined by the build plate. In this step some capabilities of scaling and basic manipulation of build part are usually provided to account for changes needed at this step. Once the physical locations of parts are decided upon, it is followed by a series of steps of defining the (1) build process parameters, (2) material parameters, and (3) Part parameters.

The build process parameter controls machine level parameter that is applied to the entire build. Examples of these parameters include gas injection processes, material recoater motions, and ventilation processes, etc. These parameters define the basic level machine operation to enable a build environment. Material parameters typically control powder dosing behaviors and chamber environment control through inert gas injection. Critical parameter such as “dose factor” determines the amount by which the dose chamber plate rises as compared with the drop in the build chamber build plate. A 100% dose factor means that the rise in the dose chamber plate is the same as the drop in the build chamber plate. Typically higher values (150–200%) are desired at the beginning of the process to ensure full coverage of a new layer with powder material. This factor needs to have values greater than 100% because as the powder is melted and fused into a solid layer, the volume occupied by the material in a solid layer form is smaller than that of in the powder form, due to elimination of spaces between powder particles. Therefore, the surface of melted areas is lower than the rest of the powder bed. As the portion of the powder bed surface occupied by build part increases, the dosing factor also needs to increase accordingly. This factor is typically adjustable anytime during a build process as well to provide adjustments to the build process as needed.

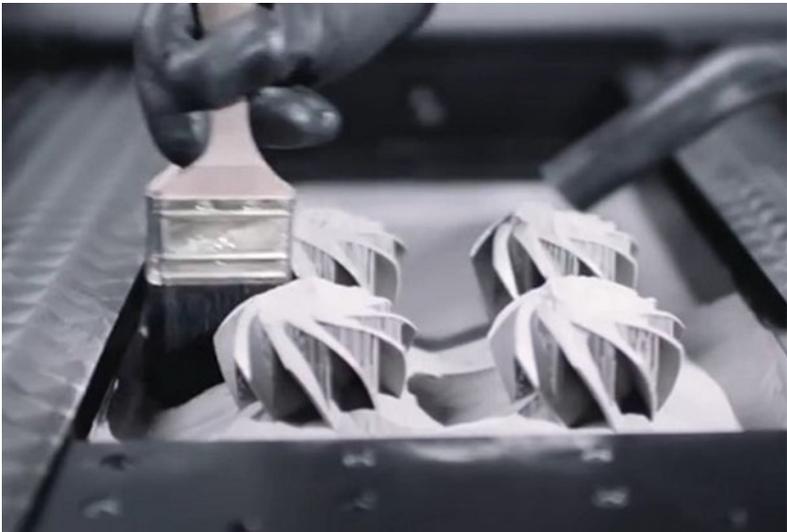
Inert gases such as nitrogen or argon are typically used in AM system to control the build chamber environment and maintain low oxygen concentration. Oxygen concentration inside the build chamber is of critical importance to not only the build quality, but also to the success of a build process. Typically the oxygen concentration is maintained below 1–2%. Upper and lower limits of concentrations are often set to allow the gas injection and ventilation system to maintain the oxygen content. Above threshold values, AM systems will shut down the build process. In reactive material (such as aluminum, titanium, etc.) powder bed processes, oxygen content control is particularly important due to safety reasons, and the inert gas injection typically remains on even after the build process ends.

Part parameters are assigned to each and every component/part to be build. Multiple sets of part parameters can be used in the same build on different parts. These parameters are taken into account in the slicing process that takes place in the previous step of the process chain. As a result, the parameters chosen in the slicer have to correspond to the actual parameters selected on the AM system. Once part parameters are selected the building process, the build process starts and is controlled and monitored by the AM system itself. Some feedback and in-process monitoring systems are possible. Most current systems are outfitted with basic in-process diagnostic tools such as melt-pool monitoring where an diagnostic beam coaxial to the process beam monitors the intensity of emission of thermal radiation from the melt-pool and does basic analysis of melt-pool size and radiation intensity spatial distribution. A quality index can be extracted from the results of monitoring to provide an indication of part quality. Another type of in-process feedback tool available to some of the current systems is related to the powder re-coating process. The tool typically takes an optical image of each and every layer and use the

reflectivity information within the optical image to determine where a full coating on a completed layer is achieved. In some cases, this value is used to pause the process to prevent failure of builds due to insufficient powder coating and over-heating.

## 2.5 Build Removal

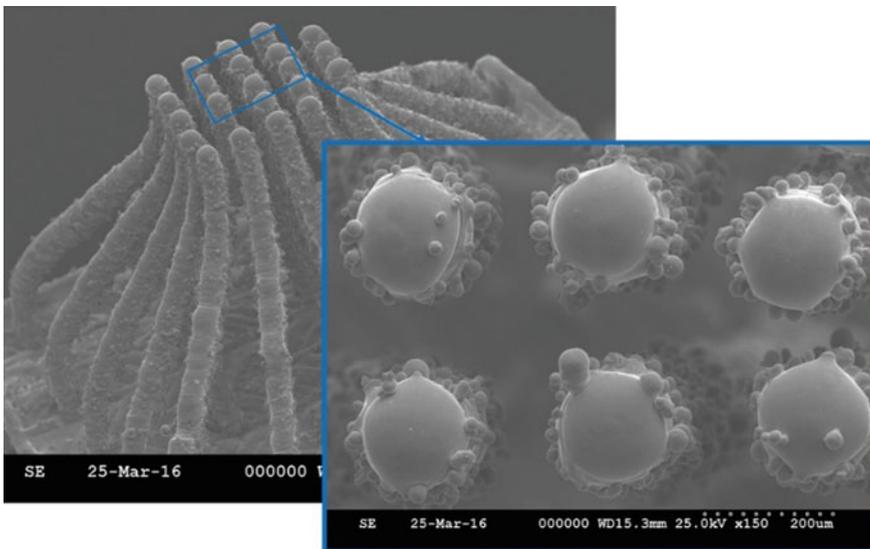
The build time of the powder bed process depends on a number of factors. Of them, the height of the entire build has the largest effect on the total time. It can take anywhere from minutes to days. Nevertheless, once the build completes, the laser metal powder bed technology allows for immediate unpacking of build chamber and retrieval of finished part, because the process does not maintain the build platform at elevated temperatures (as opposed to laser powder bed for polymers and electron beam-based powder bed processes). The unpacking process typically involves raising the platform in the build chamber and removing loose powder at the same time. The loose powder from one process can be re-used and has to go through a series of sieving steps to remove contaminants and unwanted particulates. Figure 2.4 shows an example of the process. Once the loose powder is removed from the finished part, the build is ready for post-process. The finished parts in metal powder bed AM at this point are welded onto the build plate via support structures. Removal of finished part from the build plate typically involves the use of cutting tools such as band saws, or wire EDM for higher fidelity and flexibility.



**Fig. 2.4** SLM part being extracted from build chamber. *Image source* topmaxtech.net

## 2.6 Post-processing

Depending on AM technology used to create the part, the purpose, and requirements of the finished part, the post-fabrication processes can vary in a wide range. It can require anything from no post process to several additional steps of processing to change the surface, dimensions, and/or material properties of the built part. Shown in Fig. 2.5 is an example of the unique surface features on powder bed AM parts where partially melted particles are bound to the surfaces of built parts. These features, along with the weld-lines rastering the melt-pool in different directions results in a new type of surface finish that is distinct from any existing manufacturing processes. In metal powder bed AM systems, the minimum required processing is removal of built part from build plate and the removal of support structures from the built part. Removal of support structures can be as simple as manually breaking the supports from the surface of the part, but it can also be a process that utilizes CNC tools to not only remove the support, but also to achieve desired surface finish and/or dimension tolerance. In addition, the metal powder bed AM systems can introduce large amounts of thermal stresses into the built part. Under these conditions, the support structure serves as the mechanical “tie-downs” to hold the built part in place and keep it in its intended geometry. If the supports were to be removed from the part, warpage in the part will occur. A thermal annealing process can be used to relieve the thermal stresses in the part before it is removed from the build plate, to prevent part warpage upon removal from the build plate.



**Fig. 2.5** SEM images of SLM parts showing unique surface features unlike any other current manufacturing processes

Hot Isostatic Pressing, HIP, is a process where a component is subjected to elevated temperature and isostatic pressure in a pressure vessel. At a temperature of over 50% of the melting point of materials and pressures above 100 MPa (can be as high as 300 MPa), the voids and porosity inside a powder bed metal AM part can be greatly reduced. Once processed by HP, the final bulk density can reach more than 95% of the true density of material. Under these extreme conditions of pressure and temperature, material in a component being treated not only undergoes localized plastic deformation, but the processes of creep and solid-state diffusion bonding are allowed to take place. This enables the required shaping and mass transport around internal defects to happen and to “heal” them, increasing the bulk density of the component.



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