Post-processing 14

14.1 Introduction

Most AM processes require post-processing after part building to prepare the part for its intended form, fit and/or function. Depending upon the AM technique, the reason for post-processing varies. For purposes of simplicity, this chapter will focus on post-processing techniques which are used to enhance components or overcome AM limitations. These include:

1. Support material removal
2. Surface texture improvements
3. Accuracy improvements
4. Aesthetic improvements
5. Preparation for use as a pattern
6. Property enhancements using non-thermal techniques
7. Property enhancements using thermal techniques

The skill with which various AM practitioners perform post-processing is one of the most distinguishing characteristics between competing service providers. Companies which can efficiently and accurately post-process parts to a customer's expectations can often charge a premium for their services; whereas, companies which compete primarily on price may sacrifice post-processing quality in order to reduce costs.

14.2 Support Material Removal

The most common type of post-processing in AM is support removal. Support material can be broadly classified into two categories: (a) material which surrounds the part as a naturally occurring by-product of the build process (natural supports),

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and (b) rigid structures which are designed and built to support, restrain, or attach the part being built to a build platform (synthetic supports).

14.2.1 Natural Support Post-processing

In processes where the part being built is fully encapsulated in the build material, the part must be removed from the surrounding material prior to its use. Processes which provide natural supports are primarily powder-based and sheet-based processes. Specifically, all powder bed fusion (PBF) and binder jetting processes require removal of the part from the loose powder surrounding the part; and bond-then-form sheet metal lamination processes require removal of the encapsulating sheet material.

In polymer PBF processes, after the part is built it is typically necessary to allow the part to go through a cool-down stage. The part should remain embedded inside the powder to minimize part distortion due to nonuniform cooling. The cool-down time is dependent on the build material and the size of the part(s). Once cool-down is complete, there are several methods used to remove the part(s) from the surrounding loose powder. Typically, the entire build (made up of loose powder and fused parts) is removed from the machine as a block and transported to a "breakout" station where the parts are removed manually from the surrounding powdered material. Brushes, compressed air, and light bead blasting are commonly used to remove loosely adhered powder; whereas, wood-working tools and dental cleaning tools are commonly used to remove powders which have sintered to the surface or powder entrapped in small channels or features. Internal cavities and hollow spaces can be difficult to clean and may require significant post-processing time.

With the exception of an extended cool-down time, natural support removal techniques for binder jetting processes are identical to those used for PBF. In most cases, parts made using binder jetting are brittle out of the machine. Thus, until the parts have been strengthened by infiltration the parts must be handled with care. This is also true for PBF materials that require post-infiltration, such as some elastomeric materials, polystyrene materials for investment casting, and metal and ceramic green parts.

More recently, automated loose powder removal processes have been developed. These can be stand-alone apparatuses or integrated into the build chamber. One of the first ZCorp (now 3D Systems) binder jetting machines with this capability is illustrated in Fig. 14.1. Several metal PBF machine manufacturers have started to integrate semi-automated powder removal techniques into their machines as well. Current trends suggest that many future PBF and binder jetting machines will incorporate some form of automated powder removal after part completion.

Bond-then-form sheet lamination processes, such as Mcor's machines, also require natural support material removal prior to use. If complex geometries with overhanging features, internal cavities, channels or fine features are used, the

Fig. 14.1 Automated powder removal using vibratory and vacuum assist in a ZCorp 450 machine (Courtesy Z Corporation)

Fig. 14.2 LOM support removal process (de-cubing), showing: (**a**) the finished block of material; (**b**) removal of cubes far from the part; (**c**) removal of cubes directly adjacent to the part; (**d**) the finished product (Courtesy Worldwide Guide to Rapid Prototyping web site © Copyright Castle Island Co., All rights reserved. Photo provided by Cubic Technologies.)

support removal may be tedious and time-consuming. If enclosed cavities or channels are created, it is often necessary to delaminate the model at a specific *z*-height in order to gain access to de-cube the internal feature; and then re-glue it after removing excess support materials. An example of de-cubing operation for LOM is shown in Fig. 14.2.

14.2.2 Synthetic Support Removal

Processes which do not naturally support parts require synthetic supports for overhanging features. In some cases, such as when using PBF techniques for metals, synthetic supports are also required to resist distortion. Synthetic supports can be made from the build material or from a secondary material. The development of secondary support materials was a key step in simplifying the removal of

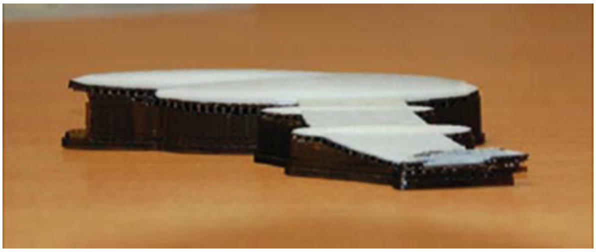

Fig. 14.3 Flat FDM-produced aerospace part. White build material is ABS plastic and black material is the water-soluble WaterWorks™ support material (Courtesy of Shapeways. Design by Nathan Yo Han Wheatley.)

synthetic supports as these materials are designed to be either weaker, soluble in a liquid solution, or to melt at a lower temperature than the build material.

The orientation of a part with respect to the primary build axis significantly affects support generation and removal. If a thin part is laid flat, for instance, the amount of support material consumed may significantly exceed the amount of build material (see Fig. 14.3). The orientation of supports also affects the surface finish of the part, as support removal typically leaves "witness marks" (small bumps or divots) where the supports were attached. Additionally, the use of supports in regions of small features may lead to these features being broken when the supports are removed. Thus, orientation and location of supports is a key factor for many processes to achieve desirable finished part characteristics.

14.2.2.1 Supports Made from the Build Material

All material extrusion, material jetting, and vat photopolymerization processes require supports for overhanging structures and to connect the part to the build platform. Since these processes are used primarily for polymer parts, the low strength of the supports allows them to be removed manually. These types of supports are also commonly referred to as breakaway supports. The removal of supports from downward-facing features leaves witness marks where the supports were attached. As a result, these surfaces may require subsequent sanding and polishing. Figure 14.4 shows breakaway support removal techniques for parts made using material extrusion and vat photopolymerization techniques.

PBF and DED processes for metals and ceramics also typically require support materials. An example of dental framework, oriented so that support removal does not mar the critical surfaces, is shown in Fig. 14.5. For these processes the metal supports are often too strong to be removed by hand; thus, the use of milling, band-saws, cut-off blades, wire-EDM, and other metal cutting techniques are widely employed. As discussed in Chap. 5, parts made using electron beam melting have fewer supports than those made using metal laser sintering, since EBM holds the part at elevated temperature throughout the build process and less residual stresses are induced.

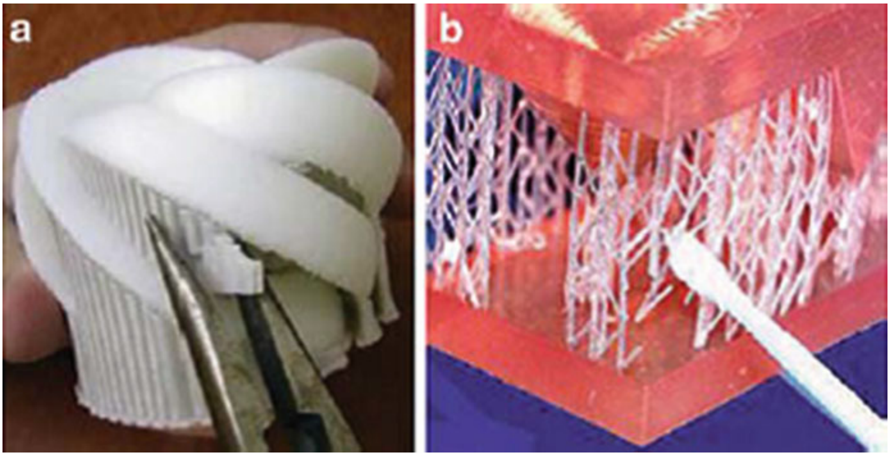

Fig. 14.4 Breakaway support removal for (**a**) an FDM part (courtesy of Jim Flowers) and (**b**) an SLA part (Courtesy Worldwide Guide to Rapid Prototyping web site. © Copyright Castle Island Co., All rights reserved. Photo provided by Cadem A.S., Turkey)

Fig. 14.5 SLM dental framework (© Emerald Group Publishing Limited) [1]

14.2.2.2 Supports Made from Secondary Materials

A number of secondary support materials have been developed over the years in order to alleviate the labor-intensive manual removal of support materials. Two of the first technologies to use secondary support materials were the Cubital layer-wise vat photopolymerization process and the Solidscape material jetting process. Their use of wax support materials enabled the block of support/build to be placed in a warm water bath; thus, melting or dissolving the wax yields the final parts.

Since that time, secondary supports have become common commercially in material extrusion (Fig. 14.3) and material jetting processes. Secondary supports have also been demonstrated for form-then-bond sheet metal lamination and DED processes in research environments.

For polymers, the most common secondary support materials are polymer materials which can be melted and/or dissolved in a water-based solvent. The water can be jetted or ultrasonically vibrated to accelerate the support removal process. For metals, the most common secondary support materials are lower-melting-temperature alloys or alloys which can be chemically dissolved in a solvent (in this case the solvent must not affect the build material).

14.3 Surface Texture Improvements

AM parts have common surface texture features that may need to be modified for aesthetic or performance reasons. Common undesirable surface texture features include: stair-steps, powder adhesion, fill patterns from material extrusion or DED systems, and witness marks from support material removal. Stair-stepping is a fundamental issue in layered manufacturing, although one can choose a thin layer thickness to minimize error at the expense of build time. Powder adhesion is a fundamental characteristic of binder jetting, PBF, and powder-based DED processes. The amount of powder adhesion can be controlled, to some degree, by changing part orientation, powder morphology, and thermal control technique (such as modifying the scan pattern).

The type of post-processing utilized for surface texture improvements is dependent upon the desired surface finish outcome. If a matte surface finish is desired, a simple bead blasting of the surface can help even the surface texture, remove sharp corners from stair-stepping, and give an overall matte appearance. If a smooth or polished finish is desired, then wet or dry sanding and hand-polishing are performed. In many cases, it is desirable to paint the surface (e.g., with cyanoacrylate, or a sealant) prior to sanding or polishing. Painting the surface has the dual benefit of sealing porosity and, by viscous forces, smoothing the stair-step effect, thus making sanding and polishing easier and more effective.

Several automated techniques have been explored for surface texture improvements. Two of the most commonly utilized include tumbling for external features and abrasive flow machining for, primarily, internal features. These processes have been shown to smooth surface features nicely, but at the cost of small feature resolution, sharp corner retention, and accuracy.

14.4 Accuracy Improvements

There is a wide range of accuracy capabilities between AM processes. Some processes are capable of submicron tolerances, whereas others have accuracies around 1 mm. Typically, the larger the build volume and the faster the build speed the worse the accuracy. This is particularly noticeable, for instance, in directed energy deposition processes where the slowest and most accurate DED processes have accuracies approaching a few microns; whereas, the larger bulk deposition machines have accuracies of several millimeters.

14.4.1 Sources of Inaccuracy

Process-dependent errors affect the accuracy of the *X*–*Y* plane differently from the *Z*-axis accuracy. These errors come from positioning and indexing limitations of specific machine architectures, lack of closed-loop process monitoring and control strategies, and/or from issues fundamental to the volumetric rate of material addition (such as melt pool or droplet size). In addition, for many processes, accuracy is highly dependent upon operator skill. Future accuracy improvements in AM will require fully automatic real-time control strategies to monitor and control the process, rather than the need to rely on expert operators as a feedback mechanism. Integration of additive plus subtractive processing is another method for process accuracy improvement.

Material-dependent phenomena also play a role in accuracy, including shrinkage and residual stress-induced distortion. Repeatable shrinkage and distortion can be compensated by scaling the CAD model; however, predictive capabilities at present are not accurate enough to fully understand and compensate for variations in shrinkage and residual stresses that are scan pattern or geometry dependent. Quantitative understanding of the effects of process parameters, build style, part orientation, support structures, and other factors on the magnitude of shrinkage, residual stress, and distortion is necessary to enhance these predictive capabilities. In the meantime, for parts which require a high degree of accuracy, extra material must be added to critical features, which is then removed via milling or other subtractive means to achieve the desired accuracy.

In order to meet the needs of applications where the benefits of AM are desired with the accuracy of a CNC machined component, a comprehensive strategy for achieving this accuracy can be adopted. One such strategy involves pre-processing of the STL file to compensate for inaccuracies followed by finish machining of the final part. The following sections describe steps to consider when seeking to establish a comprehensive finish machining strategy.

14.4.2 Model Pre-processing to Compensate for Inaccuracy

For many AM processes, the position of the part within the build chamber and the orientation will influence part accuracy, surface finish, and build time. Thus, translation and rotation operations are applied to the original model to optimize the part position and orientation.

Shrinkage often occurs during AM. Shrinkage also occurs during the post-process furnace operations needed for indirect processing of metal or ceramic green parts. Pre-process manipulation of the STL model will allow a scale factor to be used to compensate for the average shrinkage of the process chain. However, when compensating for average shrinkage, there will always be some features which shrink slightly more or less than the average (shrinkage variation).

In order to compensate for shrinkage variation, if the highest shrinkage value is used then ribs and similar features will always be at least as big as the desired geometry. However, channels and holes will be too large. Thus, simply using the largest shrinkage value is not an acceptable solution.

In order to make sure that there is enough material left on the surface to be machined, adding "skin" to the original model is necessary. This skin addition, such that there is material left to machine everywhere, can be referred to as making the part "steel-safe." Many studies have shown that shrinkage variations are geometry dependent, even when using the same AM or furnace post-processing parameters. Thus, compensating for shrinkage variation requires offsetting of the original model to guarantee that even the features with the largest shrinkage levels and all channels and holes are steel-safe.

There are two primary methods for adding a skin to the surface of a part. The first is to offset the surfaces and then recalculate all of the surface intersections. This methodology, though the most common, has many drawbacks for STL files made up of triangular facets. In answer to these drawbacks, an algorithm developed for offsetting all of the individual vertices of an STL file by using the normal vector information for the connected triangles, then reconstructing the triangles by using new vertex values, has been developed [2]. See Chap. 15 for more information on STL files and software systems to manipulate them.

In an STL file, each vertex is typically shared by several triangles whose unit normal vectors are different. When offsetting the vertices of a model, the new value of each vertex is determined by the unit normal values of its connected triangles.

Suppose $\overline{V}_{\text{offset}}$ is the unit vector from the original position to the new position of the vertex which is to be moved, and $N_1, N_2, \ldots N_n$ are the unit normal vectors of the triangles which share that vertex; $\overline{V}_{\text{offset}}$ can be calculated by the weighted mean of those unit normal vectors,

$$\overline{V}_{\text{offset}} = \sum_{i=1}^{n} W_i \overline{N}_i \tag{14.1}$$

where W_i are coefficients whose values are determined to satisfy the equation,

$$\overline{V}_{\text{offset}} \cdot \overline{N} = 1 \quad (i = 1, 2, \ldots n) \tag{14.2}$$

After solving for $\overline{V}_{\text{offset}}$, the new position P_{new} of the vertex is given by the equation,

$$P_{\text{new}} = P_{\text{orignal}} + \overline{V}_{\text{offset}} * d_{\text{offset}} \tag{14.3}$$

where d_{offset} is the offset dimension set by the user.

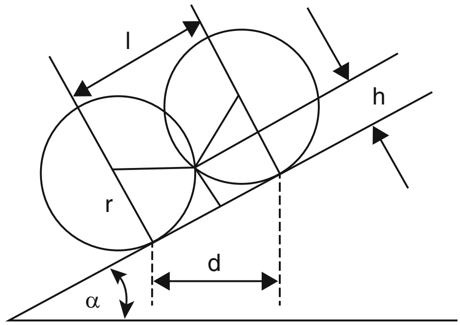

Fig. 14.6 Illustration for determining stepover distance (© Emerald Group Publishing Limited) [3]

The above procedure is repeated until the new position values for all vertices are calculated. The model is then reconstructed using the new triangle information.

Thus, to use this offset methodology, one need to only enter a d_{offset} value that is the same as the largest shrinkage variation anticipated. In practical terms, d_{offset} should be set equal to 2 or 3 times the absolute standard deviation of shrinkage measured for a particular machine/material combination.

14.4.3 Machining Strategy

Machining strategy is very important for finishing AM parts and tools. Considering both accuracy and machine efficiency, adaptive raster milling of the surface, plus hole drilling and sharp edge contour machining can fulfill the needs of most parts.

14.4.3.1 Adaptive Raster Milling

When raster machining is used for milling operations, stepover distance between adjacent toolpaths is a very important parameter that controls the machining accuracy and surface quality. It is known that higher accuracy and surface quality require a smaller stepover distance. Normally, the cusp height of material left after the model is machined is used as a measurement of the surface quality.

Figure 14.6 shows a triangle face being machined with a ball endmill. The relationship between cusp height h, cutter radius r, stepover distance d, and incline angle α is given in the following equation:

$$d = 2.0\sqrt{r^2 - (r-h)^2}\cos\alpha \tag{14.4}$$

α is determined by the triangle surface normal and stepover direction. Suppose $\overline{N}_{\text{triangle}}$ is the unit normal vector of the triangle surface, and $\overline{N}_{\text{Stepover}}$ is the unit vector along stepover direction, then

$$\cos\left(\frac{\pi}{2}-\alpha\right) = \sin\alpha = \left|\overline{N}_{\text{Triangle}}\cdot\overline{N}_{\text{Stepover}}\right| \tag{14.5}$$

From (14.4) and (14.5), the following equation for stepover distance is derived,

$$d = 2.0\sqrt{h(2r-h)\left(1-\left(\overline{N}_{\text{Triangle}}\cdot\overline{N}_{\text{Stepover}}\right)^2\right)} \tag{14.6}$$

When machining the model, the cutter radius and milling direction are the same for all triangle surfaces. If given the user-set maximum cusp height h, d is only related to the triangle normal vector. For surfaces with different normal vectors, the stepover distance obtained will be different.

If using a constant stepover distance, in order to guarantee a particular machining tolerance, the minimum calculated d should be used for the entire part. However, using the minimum stepover distances will lead to longer programs and machining times. Therefore, an adaptive stepover distance for milling operations according to local geometry should be used to allow for both accuracy and machine efficiency. This means that stepover distances are calculated dynamically for each just-finished tool pass, using the maximum cusp height to determine the stepover distance for the next tool pass.

An example of the use of this type of algorithm for tool-path generation is shown in Fig. 14.7. As can be seen, for tool paths which pass through a region of high angle, the tools paths are more closely spaced; whereas, for toolpaths that only cross relatively flat regions, the tool paths are widely spaced.

14.4.3.2 Sharp Edge Contour Machining

Sharp edges are often the intersection curves between features and surfaces. Normally, these edges define the critical dimensions. When using raster milling, the edges parallel to the milling direction can be missed, causing large errors. As shown in Fig. 14.8, when a stepover distance d is used to machine a part with slot width W, even when the CNC machine is perfectly aligned (i.e., ignoring machine positioning errors), the slot width error will be at least,

$$W_{\text{error}} = 2d - \delta_1 - \delta_2 \tag{14.6}$$

where δ_1, δ_2 represent the offset between the actual and desired edge location.

When δ_1, δ_2 become 0, $W_{\text{error}} = 2d$. This means that the possible maximum error for a slot using raster milling is approximately two times the stepover distance.

For complicated edges not parallel to the milling direction, raster milling is ineffective for creating smooth edges, as the edge will have a stair-step appearance, with the step size equal to the local stepover distance, d. Thus, after raster milling, it is advantageous to run a machining pass along the sharp edges (contours) of the part [3]. In order to machine along sharp edges, all sharp edges must first be identified from the STL model. The normal vector information of each triangle is used to check the property of an edge. The angle between normal vectors of two

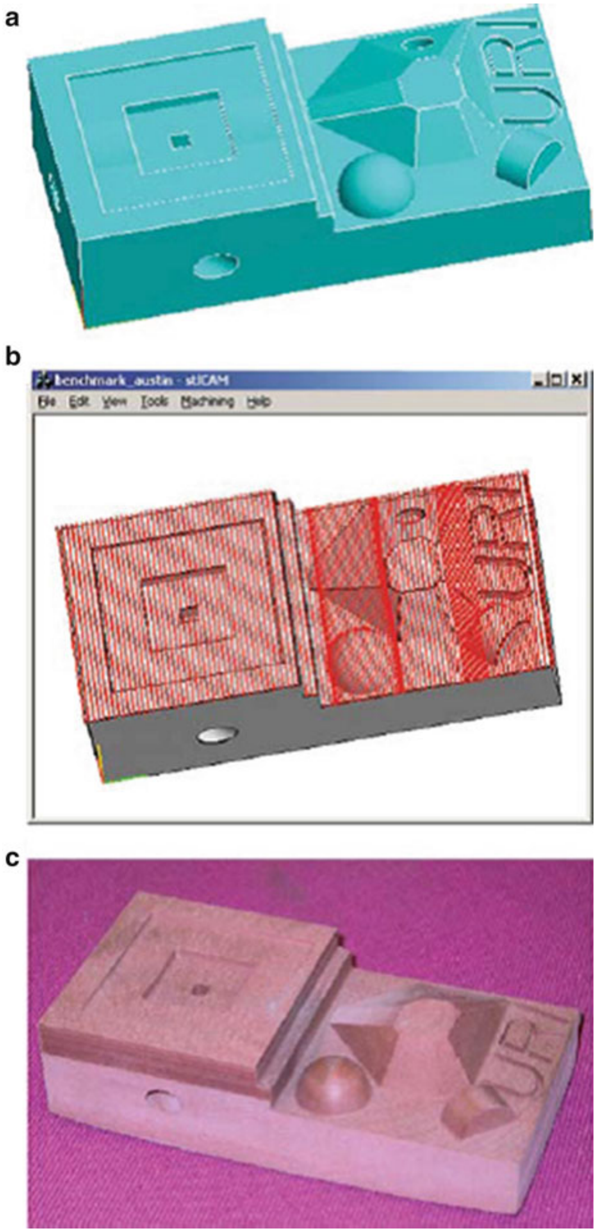

Fig. 14.7 Finish machining using adaptive raster milling of a copper-filled polyamide part made using polymer laser sintering. (**a**) CAD model, (**b**) tool paths, (**c**) machined part (© Emerald Group Publishing Limited, from "Raster Milling Tool-Path Generation from STL Files," Xiuzhi Qu and Brent Stucker, *Rapid Prototyping Journal*, 12 (1), pp. 4–11, 2006)

neighboring triangles is calculated. If this angle is larger than a user-specified angle, the edge shared by these two triangles will be marked as a sharp edge. All triangle edges are checked this way to generate a sharp edge list. Hidden edges and redundant tool paths are eliminated before tool paths are calculated. By offsetting the edges by the cutter radius, the x, y location of the endmill is obtained. The

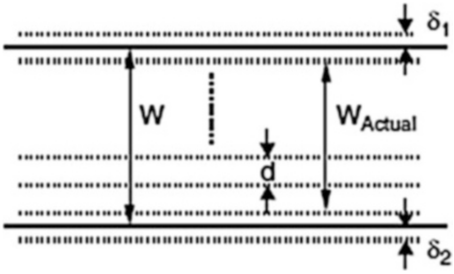

Fig. 14.8 Influence of stepover distance on dimensional accuracy (© Emerald Group Publishing Limited) [3]

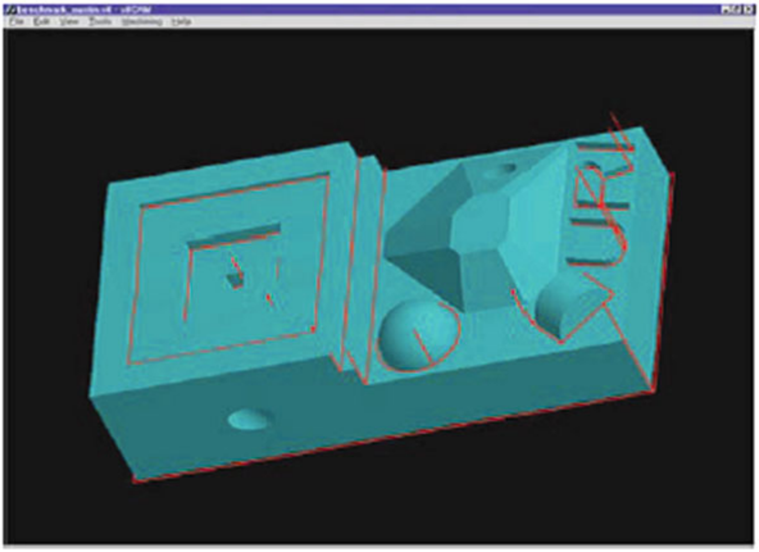

Fig. 14.9 Sharp edge contours identified for milling

z value is determined by calculating the intersection with the 3D model and finding the corresponding maximum *z* value. Using this approach, sharp edges can be identified and easily finish machined. Figure 14.9 shows the part from Fig. 14.7 with sharp edge contour paths highlighted.

14.4.3.3 Hole Drilling

Circular holes are common features in parts and tools. Using milling tools to create holes is inefficient and the circularity of the holes is poor. Therefore, a machining strategy of identifying and drilling holes is preferable. The most challenging aspect is to recognize holes in an STL or AMF file, as the 3D geometry is represented by a collection of unordered triangular planar facets (and thus all feature information is lost).

The intersection curve between a hole and a surface is typically a closed loop. By using this information, a hole recognition algorithm begins by identifying all closed loops made up of sharp edges from the model. These closed loops may not necessarily be the intersection curves between holes and a surface, so a series of hole-checking rules are used to remove the loops that do not correspond to drilled holes. The remaining loops and their surface normal vectors are used to determine the diameter, axis orientation, and depth for drilling. From this information, tool paths can be automatically generated [3].

Thus, by pre-processing an STL file using a shrinkage and surface offset value, and then post-processing the part using adaptive raster milling, contour machining, and hole drilling, an accurate part can be made. In many cases, however, this type of comprehensive strategy is not necessary. For instance, for a complex part where only one or two features must be made accurately, the part could be pre-processed using the average shrinkage value as a scaling factor and a skin can be added only to the critical features. These critical features could then be manually machined after AM part creation, leaving the other features as is. Thus, the finish machining strategy adopted will depend greatly upon the application and part-specific design requirements.

14.5 Aesthetic Improvements

Many times AM is used to make parts which will be displayed for aesthetic or artistic reasons or used as marketing tools. In these and similar instances, the aesthetics of the part is of critical importance for its end application.

Often the desired aesthetic improvement is solely related to surface finish. In this case, the post-processing options discussed in Sect. 14.2 can be used. In some cases, a difference in surface texture between one region and another may be desired (this is often the case in jewelry). In this case, finishing of selected surfaces only is required (such as for the cover art for this book).

In cases where the color of the AM part is not of sufficient quality, several methods can be used to improve the part aesthetics. Some types of AM parts can be effectively colored by simply dipping the part into a dye of the appropriate color. This method is particularly effective for parts created from powder beds, as the inherent porosity in these parts leads to effective absorption. If painting is required, the part may need to be sealed prior to painting. Common automotive paints are quite effective in these instances.

Another aesthetic enhancement (which also strengthens the part and improves wear resistance) is chrome plating. Figure 14.10 shows a stereolithography part before and after chrome plating. Several materials have been electroless coated to AM parts, including Ni, Cu, and other coatings. In some cases, these coatings are thick enough that, in addition to aesthetic improvements, the parts are robust enough to use as tools for injection molding or as EDM electrodes.

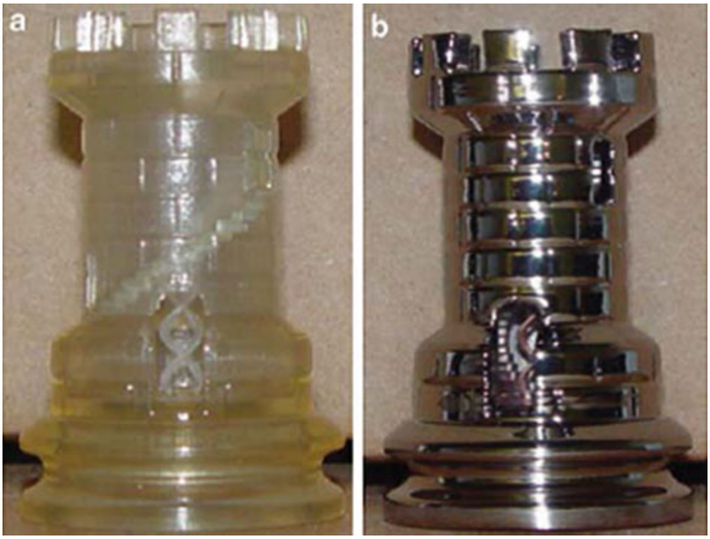

Fig. 14.10 Stereolithography part (**a**) before and (**b**) after chrome plating (Courtesy of Artcraft Plating)

14.6 Preparation for Use as a Pattern

Often parts made using AM are intended as patterns for investment casting, sand casting, room temperature vulcanization (RTV) molding, spray metal deposition, or other pattern replication processes. In many cases, the use of an AM pattern in a casting process is the least expensive way to use AM to produce a metal part, as many of the metal-based AM processes are still expensive to own and operate.

The accuracy and surface finish of an AM pattern will directly influence the final part accuracy and surface finish. As a result, special care must be taken to ensure the pattern has the accuracy and surface finish desired in the final part. In addition, the pattern must be scaled to compensate for any shrinkage that takes place in the pattern replication steps.

14.6.1 Investment Casting Patterns

In the case of investment casting, the AM pattern will be consumed during processing. In this instance, residue left in the mold as the pattern is melted or burned out is undesirable. Any sealants used to smooth the surface during pattern preparation should be carefully chosen so as not to inadvertently create unwanted residue.

AM parts can be printed on a casting tree or manually added to a casting tree after AM. Figure 14.11 shows rings made using a material jetting system. In the first

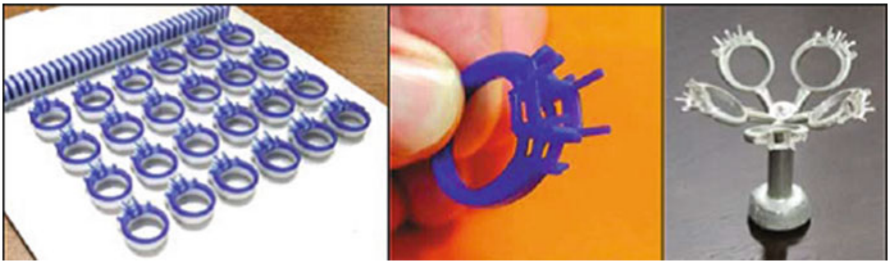

Fig. 14.11 Rings for investment casting, made using a ProJet® CPX 3D Printer (Courtesy 3D Systems)

picture, a collection of rings is shown on the build platform; each ring is supported by a secondary support material in white. In the second picture, a close-up of the ring pattern is shown. The third picture shows metal rings still attached to a casting tree. In this instance, the rings were added to the tree after AM, but before casting.

When using the stereolithography Quickcast build style, the hollow, truss-filled shell patterns must be drained of liquid prior to investment. The hole(s) used for draining must be covered to avoid investment entering the interior of the pattern. Since photopolymer materials are thermosets, they must be burned out of the investment rather than melted.

When powdered materials are used as investment casting patterns, such as polystyrene from a polymer laser sintering process or starch from a binder jetting process, the resulting part is porous and brittle. In order to seal the part and strengthen it for the investment process, the part is infiltrated with an investment casting wax prior to investment.

14.6.2 Sand Casting Patterns

Both binder jetting and PBF processes can be used to directly create sand mold cores and cavities by using a thermosetting binder to bind sand in the desired shape. One benefit of these direct approaches is that complex-geometry cores can be made that would be very difficult to fabricate using any other process, as illustrated in Fig. 14.12.

In order to prepare AM sand casting patterns for casting, loose powder is removed and the pattern is heated to complete cross-linking of the thermoset binder and to remove moisture and gaseous by-products. In some cases, additional binders are added to the pattern before heating, to increase the strength for handling. Once the pattern is thermally treated, it is assembled with its corresponding core(s) and/or cavity, and hot metal is poured into the mold. After cooling, the sand pattern is removed using tools and bead blasting.

In addition to directly producing sand casting cores and cavities, AM can be used to create parts which are used in place of the typical wooden or metal patterns around which a sand casting mold is created. In this case, the AM part is built as one

Fig. 14.12 Sand casting pattern for a cylinder head of a V6, 24-valve car engine (*left*) during loose powder removal and (*right*) pattern prepared for casting alongside a finished casting (Joint project between CADCAM Becker GmbH and VAW Südalumin GmbH, made on an EOSINT S laser-sintering machine, courtesy EOS)

or more portions of the part to be cast, split along the parting line. The split part is placed in a box, sand mixed with binder is poured around the part, and the sand is compressed (pounded) so that the binder holds the sand together. The box is then disassembled, the sand mold is removed from the box, and the pattern is removed from the mold. The mold is then reassembled with its complementary mold half and core(s) and molten metal is poured into the mold.

14.6.3 Other Pattern Replication Methods

There are many pattern replication methods which have been utilized since the late 1980s to transform the weak "rapid prototypes" of those days into parts with useful material properties. As the number of AM technologies has increased and the durability of the materials that they can produce has improved substantially, these replication processes are finding less use, as people prefer to directly produce a usable part if possible. However, even with the multiplication of AM technologies and materials, pattern replication processes are widely used among service bureaus and companies who need parts from a specific material that is not directly processable in AM.

Probably, the most common pattern replication methods are RTV molding or silicone rubber molding. In RTV molding, as shown in Fig. 14.13, the AM pattern is given visual markers (such as by using colored tape) to illustrate the parting line locations for mold disassembly; runners, risers, and gates are added; the model is suspended in a mold box; and a rubber-like material is poured around the model to encapsulate it. After cross-linking, the solid translucent rubber mold is removed from the mold box, a knife is used to cut the rubber mold into pieces according to the parting line markers, and the pattern is removed from the mold. In order to

Fig. 14.13 RTV molding process steps (Courtesy MTT Technologies Group)

complete the replication process the mold is reassembled and held together in a box or by placing rubber bands around the mold and molten material is poured into the mold and allowed to solidify. After solidification, the mold is opened, the part is removed and the process is repeated until a sufficient number of parts are made. Using this process, a single pattern can be used to make 10s or 100s of identical parts.

If the part being made in the RTV mold is a wax pattern, it can subsequently be used in an investment or plaster casting process to produce a metal part. Thus, by combining RTV molding and investment casting, one AM pattern can be replicated into a large number of metal parts for a relatively modest cost.

Metal spray processes have also been used to replicate geometry from an AM part into a metal part. In the case of metal spray, only one side of the pattern is replicated into the metal part. This is most often used for tooling or parts where one side contains all the geometric complexity and the rest of the tool or part is made up of flat edges. Using spray metal or electroless deposition processes, an AM pattern can be replicated to form an injection molding core or cavity, which can then be used to mold other parts.

14.7 Property Enhancements Using Non-thermal Techniques

Powder-based and extrusion-based processes often create porous structures. In many cases, that porosity can be infiltrated by a higher-strength material, such as cyanoacrylate (Super Glue®). Proprietary methods and materials have also been developed to increase the strength, ductility, heat deflection, flammability resistance, EMI shielding, or other properties of AM parts using infiltrants and various types of nano-composite reinforcements.

A common post-processing operation for photopolymer materials is curing. During processing, many photopolymers do not achieve complete polymerization. As a result, these parts are put into a Post-Cure Apparatus, a device that floods the part with UV and visible radiation in order to completely cure the surface and subsurface regions of the part. Additionally, the part can undergo a thermal cure in a low temperature oven, which can help completely cure the photopolymer and in some cases greatly enhance the part's mechanical properties.

14.8 Property Enhancements Using Thermal Techniques

After AM processing, many parts are thermally processed to enhance their properties. In the case of DED and PBF techniques for metals, this thermal processing is primarily heat treatment to form the desired microstructures and/or to relieve residual stresses. In these instances, traditional recipes for heat treatment developed for the specific metal alloy being employed are often used. In some cases, however, special heat treatment methods have been developed to retain the fine-grained microstructure within the AM part while still providing stress relief and ductility enhancement.

Before the advent of DED and PBF techniques capable of directly processing metals and ceramics, many techniques were developed for creating metal and ceramic green parts using AM. These were then furnace post-processed to achieve dense, usable metal and ceramic parts. Binder jetting is the only AM process which is commonly used for these purposes. The basic approach to furnace processing of green parts was illustrated in Fig. 5.7. In order to prepare a green part for furnace processing, several preparatory steps are typically done. Figure 14.14 shows the steps for preparing a metal green part made from LaserForm ST-100 for furnace infiltration.

Figure 14.15 shows an injection molding tool made from an ExOne binder jetting process after furnace debinding, sintering, and infiltration (same as Fig. 8.5). The use of cooling channels which follow the contours of the surface (conformal cooling channels) in an injection mold has been shown to significantly

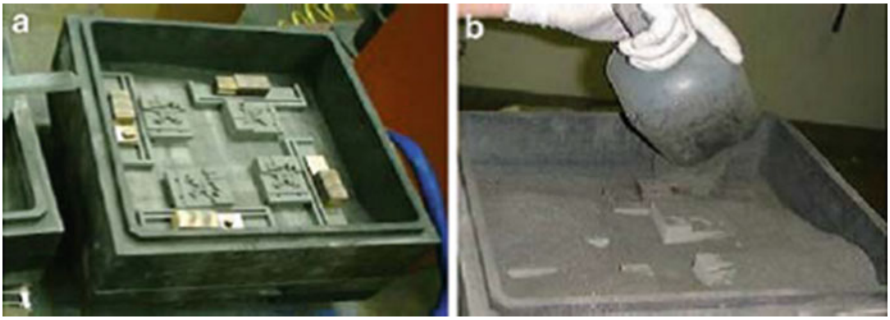

Fig. 14.14 LaserForm ST-100 green parts. (**a**) Parts are placed next to "boats" on which the bronze infiltrant is placed. The bronze infiltrates through the boat into the part. (**b**) The parts are often covered in aluminum oxide powder before placing them in a furnace to help support fragile features during debinding, sintering, and infiltration, and to help minimize thermal gradients

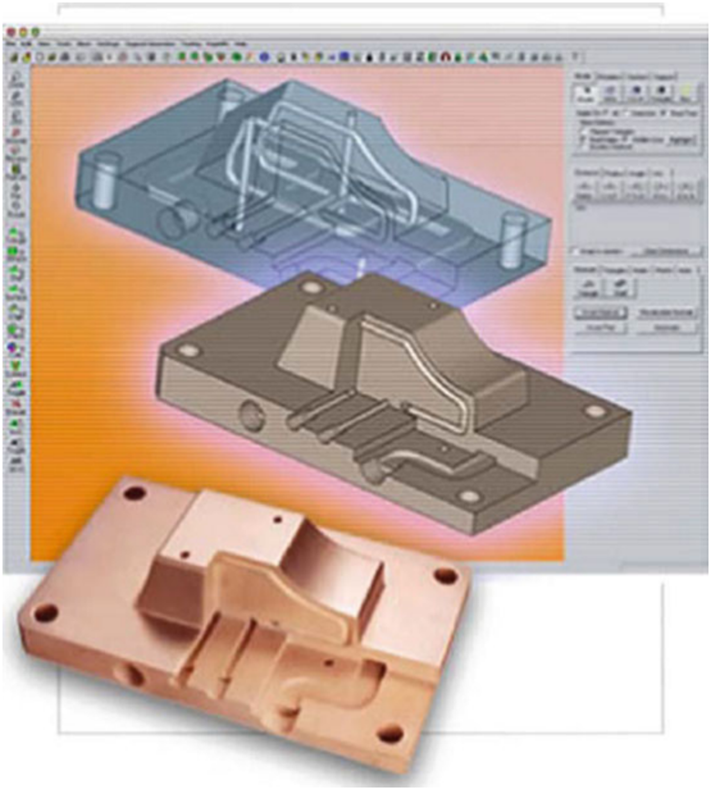

Fig. 14.15 Cross-section of a ExOne ProMetal injection molding tool showing CAD files and finished, infiltrated component with internal conformal cooling channels (Courtesy ProMetal LLC, an ExOne Company)

increase the productivity of injection mold tooling by decreasing the cooling time and part distortion. Thus, the appropriate use of conformal cooling channels enables many companies to utilize AM-produced tools to increase their productivity.

Control of shrinkage and dimensional accuracy during furnace processing is complicated by the number of process parameters that must be optimized and the multiple steps involved. Figure 14.16 illustrates the complicated nature of optimization for this type of furnace processing. The *y*-axis, $(F1–F2)/F1$ represents the dimensional changes during the final furnace stage of infiltration of stainless steel (RapidSteel 2.0) parts using bronze. $F1$ is the dimension of the brown part before infiltration and $F2$ is the dimension after infiltration. The data represent thousands of measurements across both internal (channel-like) and external (rib-like) features ranging from 0.3 to 3.0 in. Although many factors were studied, only two were found to be statistically significant for the infiltration step, atmospheric pressure in the furnace, and infiltrant amount. The atmospheric pressure ranged between 10 and 800 Torr. The amount of infiltrant used ranged from a low of 85 % to a high of

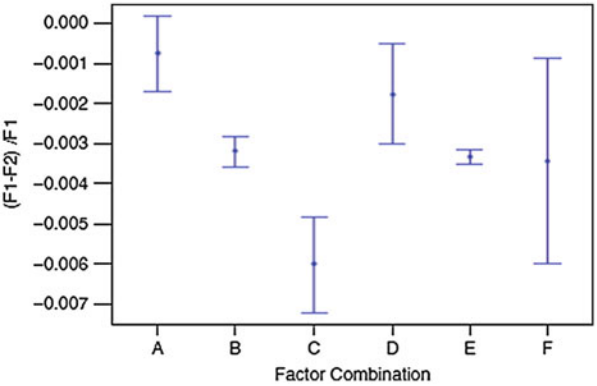

Fig. 14.16 Ninety-five percent confidence intervals for variation in shrinkage for stainless steel (RapidSteel 2.0) infiltration by bronze (Factor combinations are: (**a**) 10 Torr, 80 %; (**b**) 10 Torr, 95 %; (**c**) 10 Torr, 110 %; (**d**) 800 Torr, 80 %; (**e**) 800 Torr, 95 %; (**f**) 800 Torr, 110 %)

110 %, where the percentage amount was based upon the theoretical amount of material needed to fully fill all of the porosity in the part, based upon measurements of the weight and the volume of the part just prior to infiltration.

It can be seen from Fig. 14.16 that the factor combinations with the lowest overall shrinkage were not the factors with the lowest shrinkage variation. Factor combination A had the lowest average shrinkage, while factor combination E had the lowest shrinkage variation. As average shrinkage can be easily compensated using a scaling factor, the optimum factor combination for highest accuracy and precision would be factor combination E. If the accuracy strategy discussed in Sect. 14.3 is followed, the skin offset d_{offset} would be determined by identifying the shrinkage variation for the entire process (green part fabrication using AM, plus sintering and infiltration) using a similar approach and then setting d_{offset} equal to the maximum shrinkage variation at the desired confidence interval.

In addition to the thermal processes discussed earlier, a number of other procedures have been developed over the years to combine AM with furnace processing to produce metal or ceramic parts. One example approach utilized laser sintering to produce porous parts with gas impermeable skins. By scanning only the outside contours of a part during fabrication by SLS, a metal “can” filled with loose powder is made. These parts are then post-processed to full density using hot isostatic pressing (HIP). This in situ encapsulation results in no adverse container–powder interactions (as they are made from the same bed of powder), reduced pre-processing time, and fewer post-processing steps compared to conventional HIP of canned parts. The SLS/HIP approach was successfully used to produce complex 3D parts in Inconel 625 and Ti–6Al–4 V for aerospace applications [4].

Laser sintering has also been used to produce complex-shaped ZrB_2/Cu composite EDM electrodes. The approach involved (a) fabrication of a green part from polymer coated ZrB_2 powder using the laser sintering, (b) debinding and sintering of the ZrB_2, and (c) infiltration of the sintered, porous ZrB_2 with liquid copper. This manufacturing route was found to result in a more homogeneous structure compared to a hot pressing route.

14.9 Conclusions

Most AM-produced parts require post-processing prior to implementation in their intended use. Effective utilization of AM processes requires not only a knowledge of AM process benefits and limitations, but also of the requisite post-processing operations necessary to finalize the part for use.

When considering the intended form, fit and function for an AM-produced part, post-processing is typically required. To achieve the correct form, support material removal, surface texture improvements, and aesthetic improvements are commonly required. To achieve the correct fit, accuracy improvements, typically via milling, are commonly required. To achieve the correct function, the AM part may require preparation for use as a pattern, property enhancements using non-thermal techniques, or property enhancements using thermal techniques. Whether using automated secondary support material removal, labor-intensive de-cubing, high-temperature furnace processing, or secondary machining, choosing and properly implementing the best AM process, material and post-processing combination for the intended application is critical to success.

14.10 Exercises

1. What are the key material property considerations when selecting a secondary support material for material jetting and material extrusion? Would these considerations change when considering supporting metals deposited using a directed energy deposition process?
2. What are the primary benefits and drawbacks when offsetting triangle surfaces versus triangle vertices? (Note: You will need to find this information by finding and reading a relevant paper, as the details are not in this chapter.) Which approach would be better for freeform surfaces, such as the hood of a car or the profile of a face?
3. Assuming that the total shrinkage in an AM process is represented by Fig. 14.16, what shrinkage value and what surface offset value would you choose for pre-processing a model for each of the Factors A–F?
4. Why is contour milling beneficial for parts if adaptive raster milling ensures that all cusp heights are within acceptable values?
5. In AM processes often a larger shrinkage value is found in the *X*–*Y* plane than in the *Z* direction before post-processing. Why might this be the case?

References

1. Bibb R, Eggbeer D, Williams R (2006) Rapid manufacture of removable partial denture frameworks. Rapid Prototyping J 12(2):95–99
2. Qu X, Stucker B (2003) A 3D surface offset method for STL-format models. Rapid Prototyping J 9(3):133–141
3. Stucker B, Qu X (2003) A finish machining strategy for rapid manufactured parts and tools. Rapid Prototyping J 9(4):194–200
4. Das S et al (1999) Processing of titanium net shapes by SLS/HIP. Mater Des 20:115