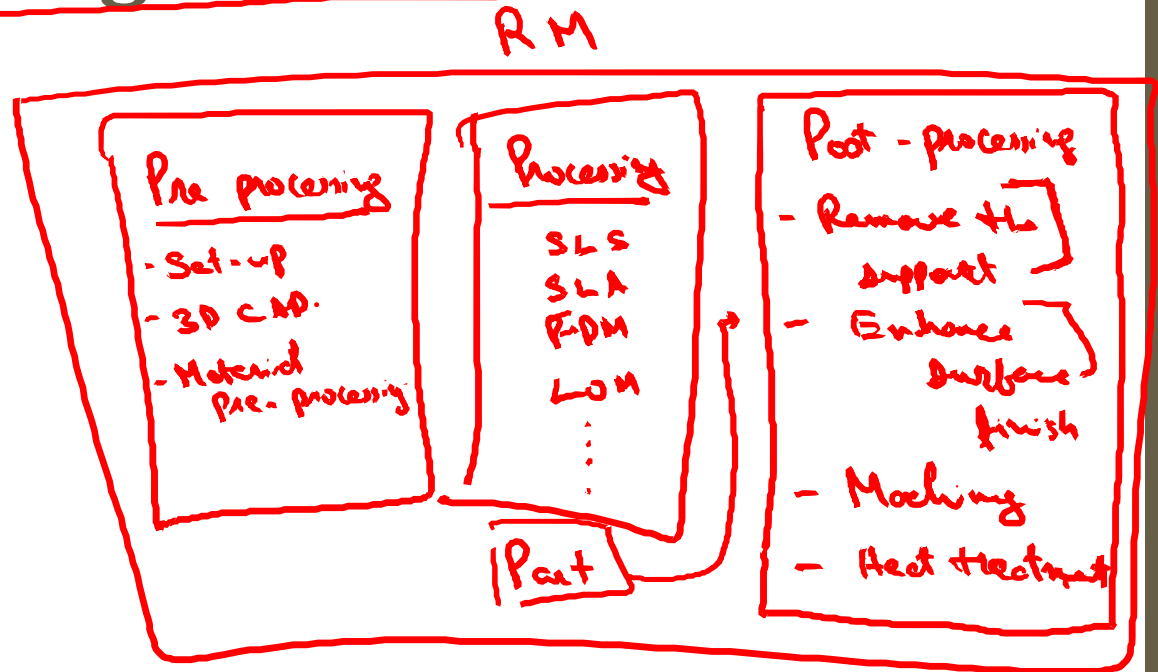


Post-processing concerns



Dr. Amandeep Singh

Department of Mechanical Engineering

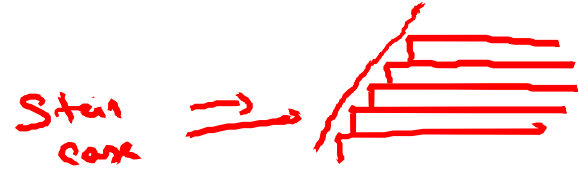
IIT Kanpur, India.

Content

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- Defects in RM parts
- **Post Processing concerns**
 - Texture Improvements
 - Accuracy ISupport Material Removal
 - Surface mprovements
 - Aesthetic Improvements
 - Preparation for use as a Pattern
 - Property Enhancements using Non-thermal Techniques
 - Property Enhancements using Thermal Techniques

Post processing

- need of..



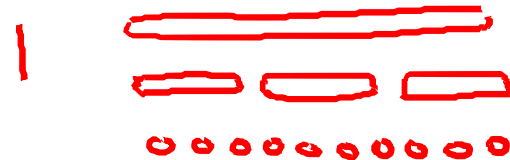
- Additive manufacturing technique helps to develop a product from the basic design of the component and to optimize the iterative product development time.
- Although AM provides many advantages over other manufacturing technologies, it still has some major drawbacks such as the staircase effect, surface quality and dimensional accuracy.
 - To improve the surface quality several attempts had been made by controlling various process parameters of Additive manufacturing and also applying different post processing techniques on components manufactured by Additive manufacturing.
- Most of the researchers worked on various post processing techniques to overcome the drawbacks.

Defects in RM parts

Reasons [Wettability
Feed A
Exclusion b

Balling:

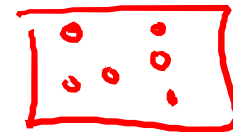
- Balling was first reported for AM in 1992 and is in fact a phenomenon that causes several physical defects such as porosity, micro-cracks or poor surface finish.
- It occurs when the liquid material fails to wet the underlying substrate (due to the surface tension), spheroidizing the liquid.
- Since contaminations can reduce the wetting degree, it is very important to prevent/minimize oxidation films and contamination.



Defects in RM parts

Porosity:

- Porosity is a common defect in AM products since most of the binding mechanisms are driven by temperature changes, gravity and capillary forces without applying external pressure.
- Porosity can be found as:
 1. Irregular pores (e.g., due to shrinkage, lack of binding/fusion/melting, or material feed shortage, often occurring at the border of molten tracks) and
 2. Spherical pores (commonly due to trapped gas, Marangoni turbulences in the melt region, material evaporation, etc., often occurring within the molten tracks).



Defects in RM parts

Cracks:

- Cracking is a serious problem in AM materials forming due to several reasons. For example, laser based AM metal-based processes (laser cladding, SLM, etc.) are known to introduce large amounts of thermal stresses, originating from the rapid shrinkage of the melt pool and/or high temperature gradients in the solid material.
- Compositional segregation and drying and shrinking of binder material are other factors that may give a rise to cracking

Low resistance
to thermal shock $\Rightarrow$ More cracking

Defects in RM parts

Distortion and delamination:

- Distortion/warpage/deflection is a defect that can originate from the stresses caused by changes in material volume (e.g., shrinkage of polymerization in stereolithography or contraction of heated plastic filament extruded in FDM) or large thermal gradients within parts.

Defects in RM parts

Poor surface finish:

- Poor surface finish originates from different factors such as the 'staircase' effect associated with
 - 1 layer thickness and building orientation, coarse deposit beads (e.g., coarse filament in FDM or large extruded chocolate beads in chocolate printers),
 - 2 low tool precision (e.g., large electron beam heat affected field in EBM),
 - 2 surface tension and balling (as common in powder bed fusion methods),
semi-melted powders (e.g., powder and support material attached to down-facing surfaces in SLM).
- Poor surface finish can even be caused by aging of the used material, e.g., the extensively used polyamide powders in SLS may lead to poor surface quality appearing as an orange peel surface.
- Poor surface finish of complex AM components may necessitate post AM treatments such as grit blasting, mechanical grinding, laser polishing, chemical etching, etc., increasing the production cost

Defects in RM parts

Chemical degradation and oxidation:

- In many AM processes (especially those subjected to a high temperature), atmospheric conditions (such as oxygen content, humidity, etc.) must be strictly controlled.
- In addition to the atmospheric conditions, processing parameters such as higher energy input or working temperature can also increase chemical degradation and oxidation.
 - For example, higher laser energies in SLS of some polymers may lead to an unwanted smoking from degradation and depolymerization of the products, reducing the mechanical properties.

Issues in metal RM parts

1. Attraction for atmosphere constituents:

Al_2O_3 layer over Al parts
Mg (highly exothermic reaction with O_2)

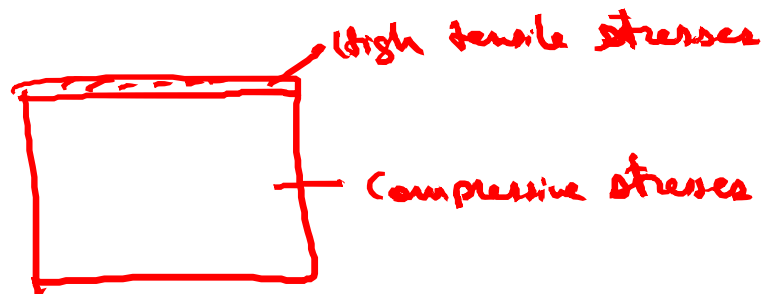
2. High reflectivity and thermal conductivity

Al
Mg
Cu

Cu

} Hampers the laser absorption

3. Residual stress:



Support Material Removal

- The most common type of post-processing in AM is support removal. Support material can be broadly classified into two categories:

1. Natural supports :
2. Synthetic supports :

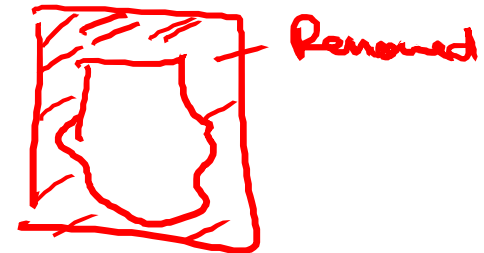
Support Material Removal

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.

Remove powder

Encapsulated sheet

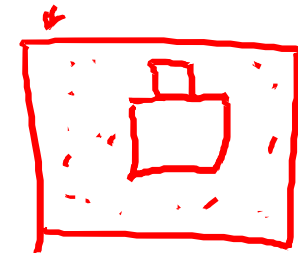


Support Material Removal

Natural Support Post-Processing

- In 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 non-uniform cooling.
- Once cool-down is complete, there are several methods used to remove the part(s) from the surrounding loose powder.

Support Material Removal



Natural Support Post-Processing

- 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.
- ¹Brushes, ²compressed air, and ³light bead blasting are commonly used to remove loosely adhered powder; whereas, ⁴wood-working tools and ⁵dental cleaning tools are commonly used to remove powders which have sintered to the surface or powder entrapped in small channels or features.

Support Material Removal

Natural Support Post-Processing

- With the exception of an extended cool-down time, natural support removal techniques for binder printing processes are identical to those used for PBF.
- In most cases, parts made using binder printing are brittle out of the machine.

Support Material Removal

Natural Support Post-Processing

- 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.
- Automated loose powder removal processes have been developed.

Support Material Removal

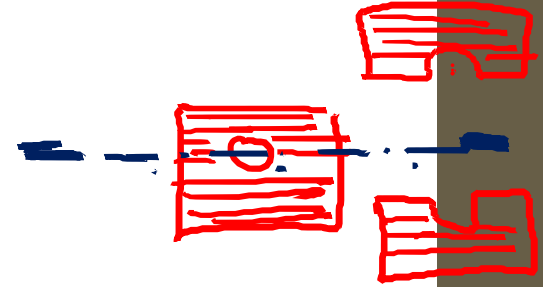
Natural Support Post-Processing

Automated powder removal using vibratory and vacuum assist in a ZCorp 450 machine.



Source: Gibson et al., Additive Manufacturing Technologies, 2010

Support Material Removal



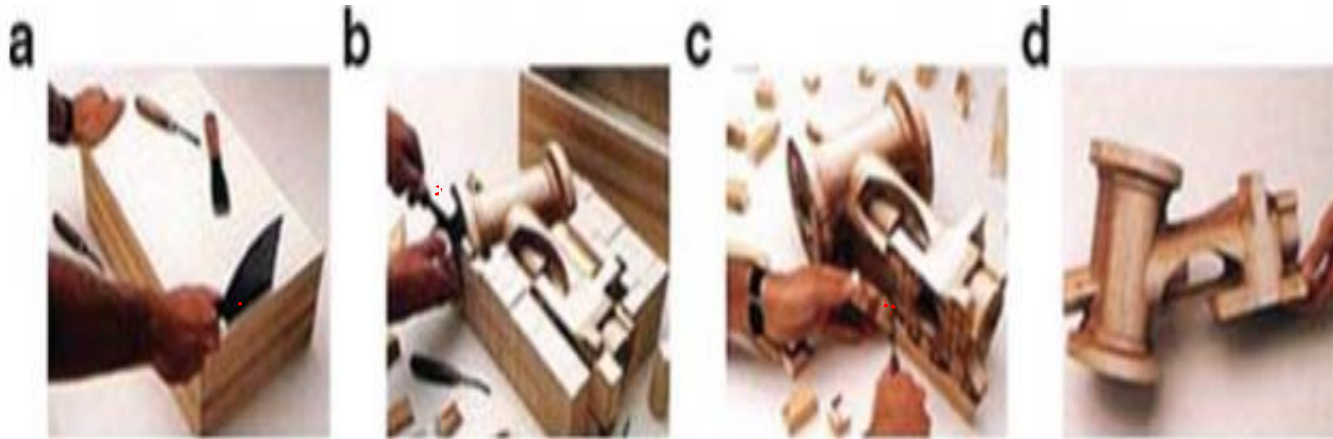
Natural Support Post-Processing

- Bond-then-form sheet lamination processes, such as laminated object manufacturing, also require natural support material removal prior to use.
- If complex geometries with overhanging features, internal cavities, channels or fine features are used, the support removal may be tedious and time-consuming.
- If 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.

Support Material Removal

Natural Support Post-Processing

LOM support removal process (de-cubing) process, 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



Source: Gibson et al., Additive Manufacturing Technologies, 2010

Support Material Removal

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.

Support Material Removal

Synthetic Support Removal

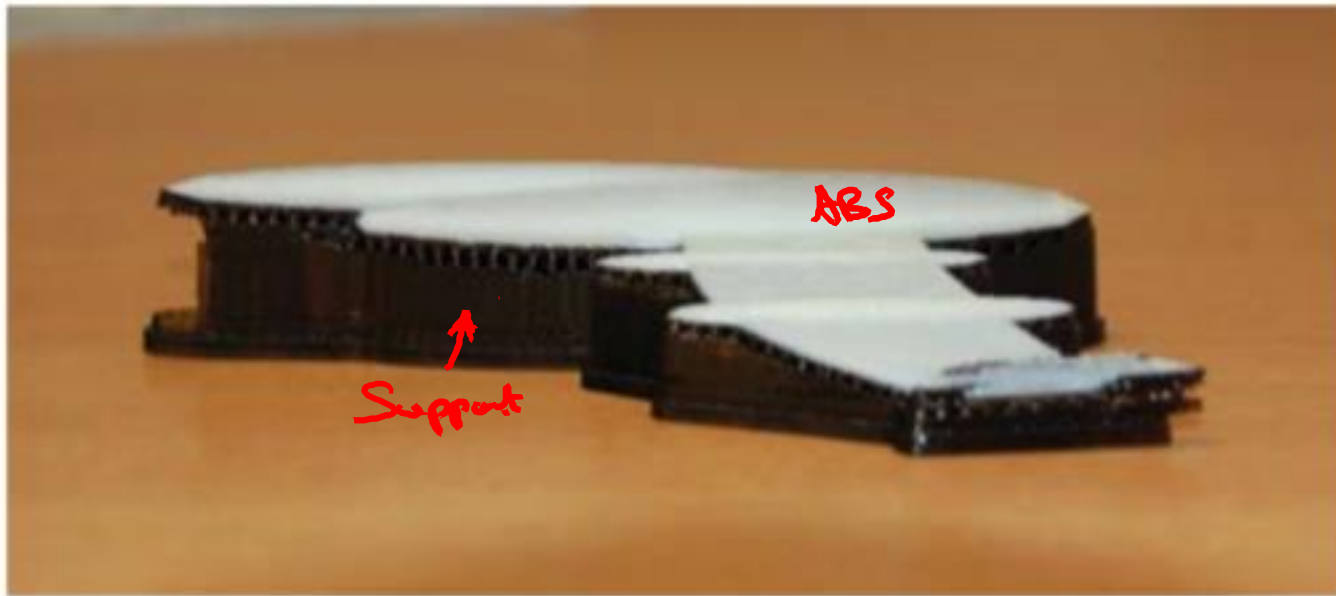
- The orientation of a part with respect to the primary build axis significantly affects support generation and removal.
- The orientation of supports also affects the surface finish of the part, as support removal typically leaves “witness marks” (small bumps or divots) where the supports were attached.

Support Material Removal

Synthetic Support Removal

Flat FDM-produced aerospace part.

White build material is ABS plastic and black material is the water-soluble WaterWorks™ support material.



Source: Gibson et al., Additive Manufacturing Technologies, 2010

Surface Texture Improvements

- AM parts have common surface-texture features that may need to be modified for aesthetic or performance reasons.
- Common surface textures are:
 - stair-steps;
 - powder adhesion;
 - fill patterns from extrusion or beam-based systems; and
 - witness marks from support material removal.

Surface Texture Improvements

Surface roughness of AM technique

Sl. no.	Name of process	Minimum layer thickness, mm	Surface roughness (Ra), μm
1	<u>SLA</u>	<u>0.10</u>	<u>2-40</u>
2	<u>SLS</u>	<u>0.125</u>	<u>5-35</u>
3	<u>FDM</u>	<u>0.254</u>	<u>9-40</u>
4	<u>3D printing (3DP)</u>	<u>0.175</u>	<u>12-27</u>
5	LOM	0.114	6-27
6	Poly jetting process	<u>0.10</u>	<u>3-30</u>

0.01 mm

0.2 μm

Surface Texture Improvements

- The amount of powder adhesion can be controlled, to some degree, by changing part orientation, powder morphology and thermal control technique.
- The type of post-processing utilized for surface texture improvements is dependent upon the desired surface finish outcome.

Surface Texture Improvements

- 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:
 1. Tumbling for external features and
 2. Abrasive flow machining for, primarily, internal features.

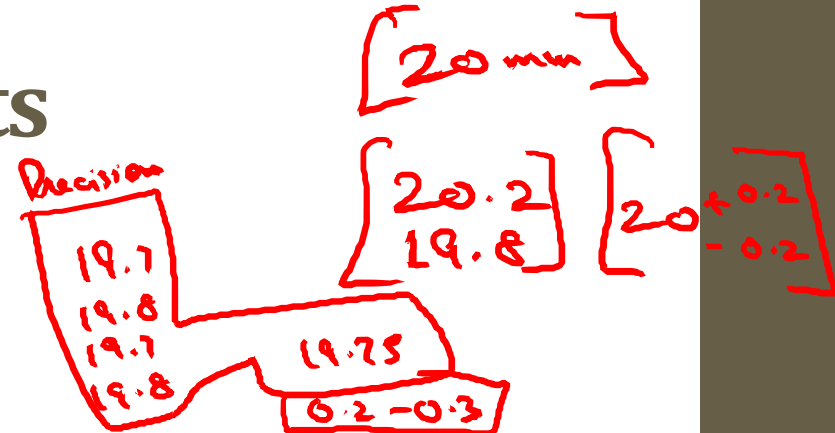
Accuracy Improvements

Seed Volume $\uparrow \Rightarrow$ Accuracy $\downarrow$

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

Accuracy Improvements

Error Sources



- Process-dependent errors affect the accuracy of the X-Y plane differently from the Z-axis accuracy.
- 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.
- Material-dependent phenomena also play a role in accuracy, including shrinkage and residual stress-induced distortion.

Accuracy Improvements

Error Sources

- Repeatable shrinkage and distortion can be compensated for 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.
- 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.

Accuracy Improvements

Model Pre-processing

- 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 postprocess furnace operations needed for indirect processing of metal or ceramic green parts.

Accuracy Improvements

Model Pre-processing

[CAE]

- 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.
- 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.

Accuracy Improvements

Model Pre-processing

- 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.

Accuracy Improvements

Machining Strategy

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.

Accuracy Improvements

Machining Strategy

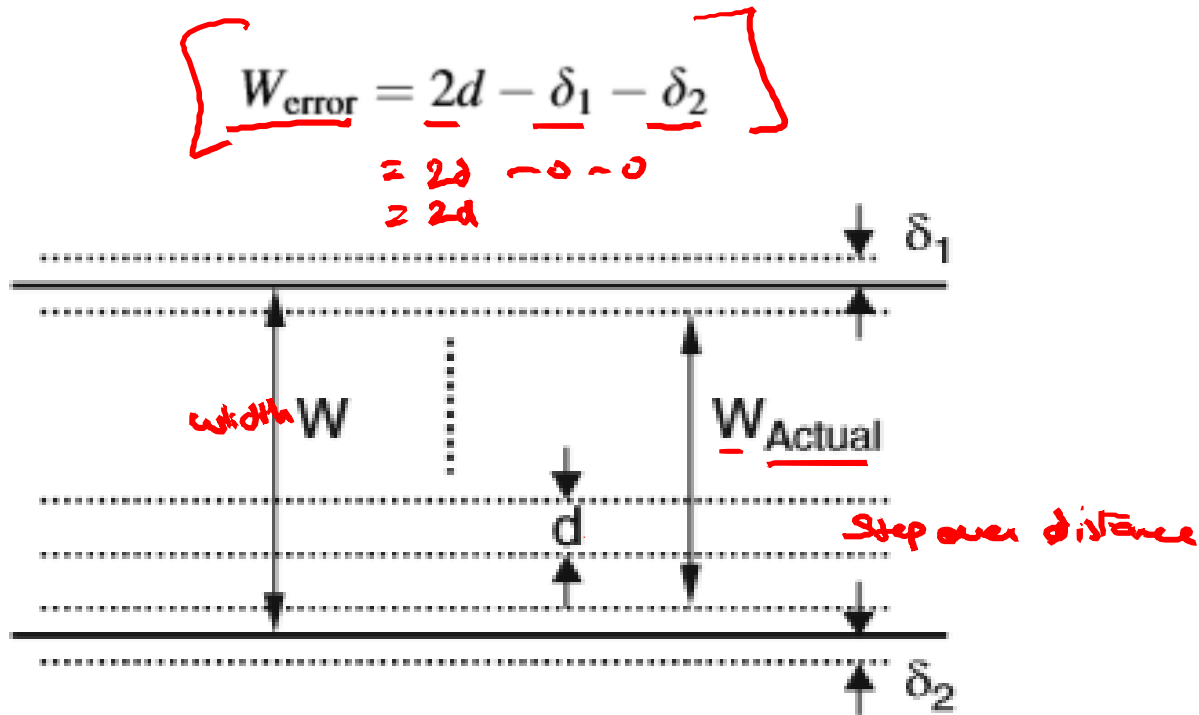
2. Sharp Edge Contour Machining

- 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.

Accuracy Improvements

Machining Strategy

Influence of stepover distance on dimensional accuracy



Source: Gibson et al., Additive Manufacturing Technologies, 2010

Accuracy Improvements

Machining Strategy

- 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.

Accuracy Improvements

Machining Strategy



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 file, as the 3D geometry is represented by a collection of unordered triangular planar facets (and thus all feature information is lost).

Accuracy Improvements

Machining Strategy

- 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.

Aesthetic Improvements

- In this case, the post-processing options discussed in above slides 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.

Aesthetic Improvements

- 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.
- 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.

Aesthetic Improvements

SLA part (a) before and (b) after chrome plating



Source: Gibson et al., Additive Manufacturing Technologies, 2010

Preparation for use as a Pattern

- The use of an AM pattern for metal part creation using a secondary molding or casting process is often 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.

Preparation for use as a Pattern

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.

Preparation for use as a Pattern

Investment Casting Patterns

Rings for investment casting, made using a ProJet1 CPX 3D Printer



Source: Gibson et al., Additive Manufacturing Technologies, 2010

Preparation for use as a Pattern

Sand Casting Patterns

- Both binder printing 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.
- 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.

Preparation for use as a Pattern

Sand Casting Patterns

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.



Source: Gibson et al., Additive Manufacturing Technologies, 2010

Property Enhancements

- 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.
- Newer, proprietary methods and materials have also been developed to strengthen various AM parts.

RP tempering Enhanced

- strength
- ductility
- heat deflection
- flammability resistance

Property Enhancements

- Non-thermal techniques

- A common post-processing operation for photopolymer materials is curing.
- During processing, many photopolymerization processes 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 completely cure the photopolymer and in some cases greatly enhance the part's mechanical properties.

Property Enhancements

- Thermal techniques

- After AM processing, many parts are thermally processed to enhance their properties.
- In the case of beam deposition 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 commonly used.

Property Enhancements

- Thermal techniques

- Before the advent of beam deposition 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.
- In order to prepare a green part for furnace processing, several preparatory steps are typically done.

To recapitulate

- What are various defects in Rapid Manufacturing parts?
- How to remove Support Material?
- Surface Texture Improvements
- Accuracy Improvements
- Aesthetic Improvements
- Preparation for use as a Pattern
- Property Enhancements using Non-thermal Techniques
- Property Enhancements using Thermal Techniques

Thanks