



Designation: F3530 – 22

## Standard Guide for Additive Manufacturing — Design — Post-Processing for Metal PBF-LB<sup>1</sup>

This standard is issued under the fixed designation F3530; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

### 1. Scope

1.1 This document provides guidance to designers who are considering the use of metal Laser Powder Bed Fusion (PBF-LB) method for their products. This guide outlines the following post-processing operations that can be considered after completion of a build on a metal additive manufacturing system:

- 1.1.1 Powder removal,
- 1.1.2 Thermal post-processing,
- 1.1.3 Build platform removal,
- 1.1.4 Support removal,
- 1.1.5 Machining, and
- 1.1.6 Surface finishing.

1.2 The topics of non-destructive testing (NDT) and inspection are beyond the scope of this document as it requires a comprehensive guide in its own right. Also, outside the scope are other metal PBF processes such as powder bed fusion – electron beam (PBF-EB) and hybrid additive manufacturing (methods combining additive manufacturing and subtractive manufacturing technologies in a single machine).

1.3 With respect to existing ISO/ASTM standards, this guide is positioned between ISO/ASTM 52910 and process-specific design guidelines such as ISO/ASTM 52911-1.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

<sup>1</sup> This guide is under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.04 on Design.

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### 2. Referenced Documents

2.1 The following existing standards are relevant to additive manufacturing (AM) design.

2.2 *ISO/ASTM Standards:*<sup>2</sup>

- 52900 Additive manufacturing — General Principles — Fundamental and vocabulary
- 52910 Additive manufacturing — Design — Requirements, guidelines and recommendations
- 52911-1 Additive manufacturing — Design — Part 1: Laser-based powder bed fusion of metals

### 3. Terminology

3.1 Terminology relating to additive manufacturing in ISO/ASTM 52900 shall apply.

3.2 *Acronyms:*

- 3.2.1 3D—3-dimensional
- 3.2.2 AM—additive manufacturing
- 3.2.3 CAD—computer aided design
- 3.2.4 CMM—coordinate measurement machine
- 3.2.5 CNC—computerized numerical control
- 3.2.6 ECM—electro-chemical machining
- 3.2.7 EDM—electrical discharge machining
- 3.2.8 FEA—finite element analysis
- 3.2.9 HAZ—heat affected zone
- 3.2.10 HIP—hot isostatic pressing
- 3.2.11 LM—laser melting
- 3.2.12 PBF-LB—powder bed fusion – laser beam
- 3.2.13 NDT—non-destructive testing
- 3.2.14 RFPE—reference free part encapsulation
- 3.2.15 XCT—X-ray computed tomography

<sup>2</sup> For referenced ASTM standards, visit the ASTM website, [www.astm.org](http://www.astm.org), or contact ASTM Customer Service at [service@astm.org](mailto:service@astm.org). For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

#### 4. AM Process Workflow

4.1 Similar to other production methods, the first step in the AM workflow begins with an idea of the part to build. An AM part must start in a software that describes its geometry.

4.1.1 Commonly, the AM process workflow is often perceived to be as simple as modelling the CAD geometry and transferring it to the machine to obtain the final part. In practice, there are a number of other key steps involved in the process as illustrated in Fig. 1. Although the workflow is illustrated linearly, this is often iterative, for example, lessons learned from a preliminary build or post-process feedback into a new iteration of the design for manufacture or build preparation. See ISO/ASTM 52910 for more detail.

4.1.2 AM has its own manufacturing constraints. Therefore, the next stages consider reducing risk in the design for the specific AM process.

4.1.3 Once the part is built, it is post-processed. This generally involves de-powdering, thermal post-processing, build platform and support removal, machining critical interfaces (if required) and surface finishing etc.

4.1.4 Finally, the part could be inspected using various contact and non-contact methods such as structured light/laser scanning, XCT and CMM etc. These steps are outside the scope of this document.

#### 5. The Importance of Design for AM Post-Processing

5.1 To design optimum parts to be built using AM, consideration must be given to the manufacturing process. Every step downstream in the process should be considered during the design stage (even if it is being outsourced to a bureau service) to ensure a suitable outcome is achieved. Fig. 2 depicts some of the downstream requirements to be taken into consideration in the design phase. Taking care of these requirements will not only improve the final product but also reduce the associated health and safety risks due to powders, part design, and operators exposure to machines when post-processing.

5.2 If the build and post-processing requirements are not considered at the design stage, there is a higher likelihood that redesigns and rebuilds of the part may be necessary. The consequences of a redesign or rebuild may include:

5.2.1 Increased costs due to failed builds or repeated builds due to quality issues.

5.2.2 Reduced functionality, for example, as-built surface roughness or parts not to tolerance.

5.2.3 Wasted resources if builds fail and parts have to be scrapped.

5.2.4 Waste of material and resources from support structures and sacrificial build features.

5.2.5 Time delays caused by unsuccessful builds or excessive post-processing.

5.3 Most AM parts will need some form of post-processing after the actual ‘build’ process has taken place. Depending on the AM process used, the geometry of a part, and the desired properties, different post-processing may be needed. Typical operations carried out after a metal PBF-LB build are described in the next sections with their challenges and design considerations. Description of how each process is carried out with common methods can be found in the appendix.

#### 6. Powder Removal

##### 6.1 Background:

6.1.1 PBF processes fill the whole volume of the build chamber with powder during a build, irrespective of the part’s geometry. Therefore, once the AM build is complete, the part must be removed from the powder and will require de-powdering. The removed powder can be sieved and recycled for the next build.

6.1.2 Powder removal may also be critical to eliminate contamination of other systems or patient requirements for implanted parts.

##### 6.2 Challenges in Powder Removal:

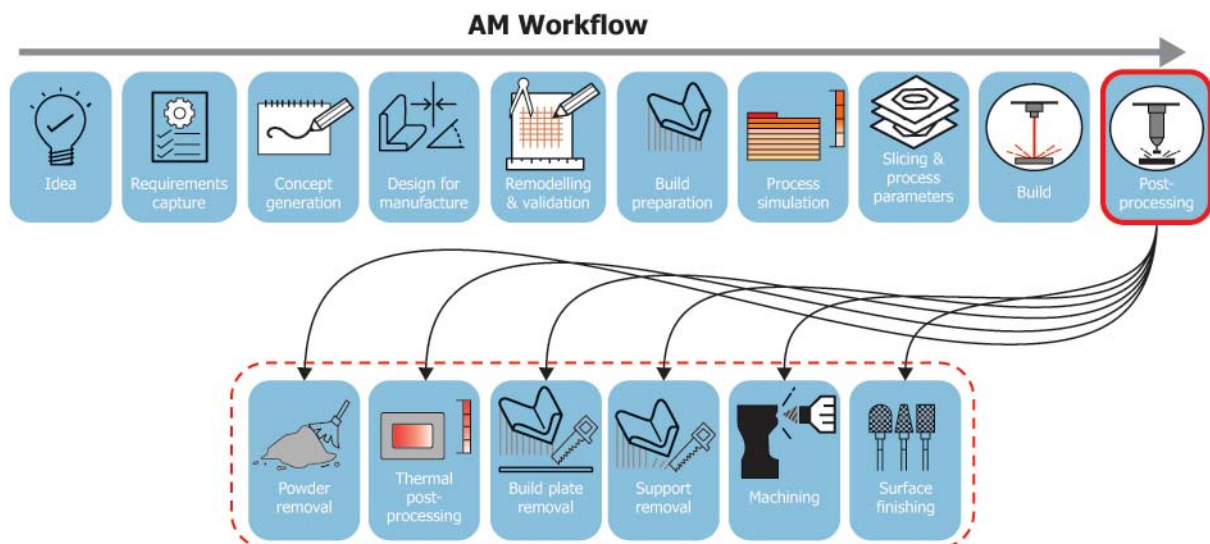


FIG. 1 Typical AM Workflow and Post-Processing Steps (Copyright MTC, all rights reserved)

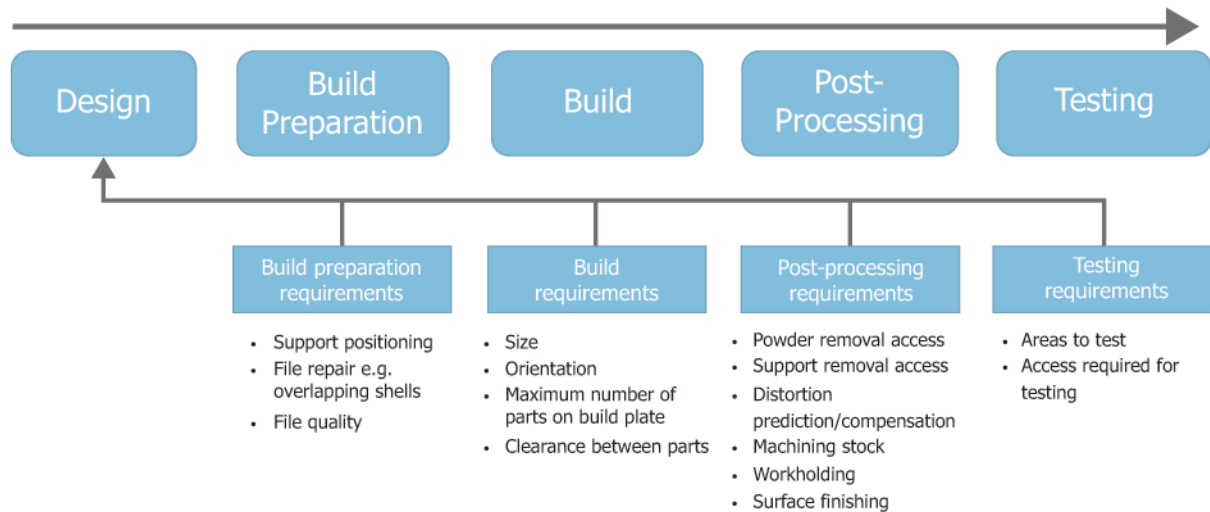


FIG. 2 AM Workflow—Input of the AM Downstream Processes to be Considered at the Design Stage (Copyright MTC, all rights reserved)

6.2.1 Residue powder can pose a health and safety issue due to the risk of ignition, inhalation, and ingestion. It can also interfere with post-processing methods such as wire EDM. See 9.4 for more detail. Residual powder can also fuse together during HIP or stress relief processes as well as consolidate after getting wet and drying after build platform removal with wire EDM or band saw.

6.2.2 Hollow parts built with PBF-LB fusion will be full of loose powder when removed from the build chamber. The lack of powder removal features such as holes, internal channels, lattice structures, slots or clearances can hinder this operation causing trapped powder. This risk can be reduced by appropriate part design together with robust cleaning methods and part inspection. Borescope or XCT inspection methods are often used to identify trapped powder in these features.

6.2.3 The choice and method of powder removal can be a challenge. A combination of blasting medium (for example, argon, sodium bicarbonate etc.) and cleaning solutions/methods (for example, deionised water, ultrasonic) might be needed. The choice of cleaning solution can also be made more difficult if CNC machining fluids must be removed. Compatibility of the cleaning solution to the material might be critical. The cleaning process may also be used to passivate the part.

### 6.3 Mitigating Powder Removal Challenges by Design:

6.3.1 The design must include powder release features, such as holes and slots that are sufficient for adequate powder removal. Table 1 displays a list of design adjustments for powder removal and offers some suggestions for how to adopt a design to ease the process. Note that the orientation of the examples is not defined, with the aim to illustrate generic powder removal situations without the influence of the support removal considerations described in 9.4.

6.3.2 An example of a part being redesigned for powder removal can be seen in the following figures. Fig. 3 shows the part placed on the build platform in the desired build orientation. Assuming the powder is not removed by powder vacuum, it will require the build platform to be tilted by a large angle to ensure proper removal of powder. The geometry of the part will

enclose a large volume of powder in the center of it. This will be very heavy and may make it difficult or even hazardous to tilt the part by hand. Moreover, such a tilt operation will put unwanted loads on the part walls. Some platforms are implementing a suction system to remove powder from within the enclosed volume to minimize exposure to powder during powder removal.

6.3.3 In Fig. 4, slots have been added to the part where it meets the build platform for ease of powder removal; this allows powder to be removed with minimal tilting. The number of slots allows powder to be removed quickly. Slots are built into stock added to the bottom of the part. This stock will be removed with wire EDM after building, meaning the finished part will be the same as before the redesign.

6.4 Design for Powder Removal Checklist—See Table 2.

## 7. Thermal Post-Processing

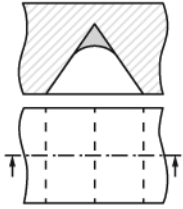
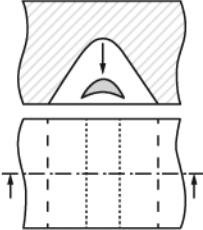
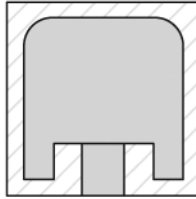
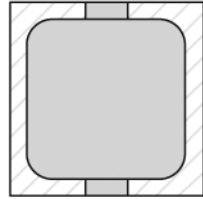
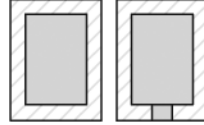
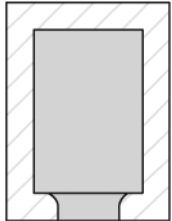
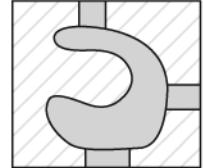
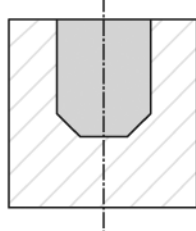
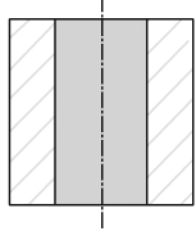
### 7.1 Background

7.1.1 Thermal post-processing of PBF-LB parts is carried out for two reasons:

7.1.1.1 *Reduce Residual Stresses*—High local heat input causes material expansion which is constrained, due to the rapid solidification rates in the surrounding material. This constraint induces residual stresses and can lead to part distortion. The continuous melting and re-melting of previously solidified layers also causes residual stress. In PBF-LB, stresses in the center of the material are typically compressive compared to stresses towards the edge which are generally tensile.

7.1.1.2 Due to the nature of the build process of PBF-LB, the as-built component may not immediately meet the design requirements for their intended application. The feedstock, build atmosphere, and processing parameters all affect the generation of defects. In particular, the repeated re-melting of the material can cause undesirable material properties and microstructure, with as-built structures likely to contain excessive porosity and lack of fusion defects. Thermal post-processing aims to alleviate or minimize defects and improve

TABLE 1 Design Adjustments for Powder Recovery (Content adapted from Kranz et al, Ref (1)<sup>A</sup>)

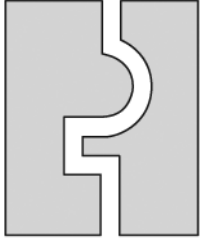
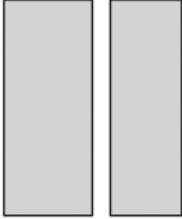
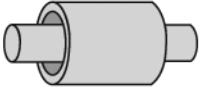
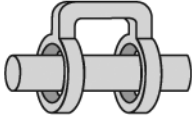
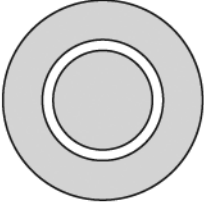
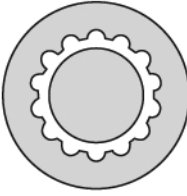
| Consideration                   | Before adjustments                                                                  | After adjustments                                                                    | Design Notes                                                                                                                                     |
|---------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Inner edge radii</b>         |    |    | Sharp inner edges should be avoided so surfaces do not need underpinning with support structures.<br><br>This allows for easier powder removal.  |
| <b>Cavity geometry</b>          |    |    | Powder nesting can be avoided by designing simple geometries with no places for powder to be trapped.                                            |
| <b>Cavity opening</b>           |   |   | For powder removal, a cavity must have at least one opening.<br><br>Larger openings will make powder removal easier.                             |
| <b>Cavity multiple openings</b> |  |  | Complex cavity geometry might require multiple openings to prevent powder nesting.                                                               |
| <b>Holes</b>                    |  |  | Through-holes are preferable over blind holes for powder removal from both sides, especially in holes with high aspect ratio and small diameter. |

the material properties. Note that the particular thermal processes used for post-processing vary for material and build process. Table 3 summarizes the thermal processes and their effects.

7.1.2 Common problems in PBF-LB as-built structures which may be reduced by thermal post-processing include:

7.1.2.1 *Porosity*—Occurs due to entrapped gas or lack-of-fusion due to irregular powder shape, insufficient material spreading or insufficient heat (Fig. 5). Gas trapped in powders from the atomization powder may also cause porosity. Lack of fusion defects often occur due to unsuitable build parameters and so thermal processing should be a last resort to these

TABLE 1 Continued

| Consideration      | Before adjustments                                                                 | After adjustments                                                                   | Design Notes                                                                                                                          |
|--------------------|------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|
| <b>Gap form</b>    |   |   | Complex gap forms should be avoided to ease powder removal.<br><br>Allowable gap varies by material, machine, and process parameters. |
| <b>Gap area</b>    |   |   | Gap areas should be designed as small as possible.<br><br>This reduces powder adhesion.                                               |
| <b>Gap grooves</b> |  |  | Consider using grooves at large gap geometries to ease powder removal                                                                 |

<sup>A</sup> The boldface numbers in parentheses refer to the list of references at the end of this standard.

defects. Keyhole porosity occurs due to bubbles of gas getting trapped underneath the surface of a part causing spherical pores under the surface. Shrinkage porosity may also occur upon solidification of liquid metal due to volume reduction. Reactive powders are sensitive to ambient humidity and may absorb moisture from surrounding air causing poor build quality.

**7.1.2.2 Cracking**—Occurs due to many factors such as insufficient material being available during solidification due to low material feed or powder scattering due to laser intensity or insufficient re-melting of previous layers occurs (Fig. 6).

**7.1.2.3 Undesirable Microstructure**—Re-melting of previous layers can lead to long, columnar grains. Depending on the material, distance from substrate and the processing parameters, the previous layer will be partially re-melted with the un-melted portion acting as a substrate for the growth of grains. Since grain growth follows the thermal gradient of the build, smaller, equiaxed grains are often found at the top layer due the slower cooling rate and no re-melting. Volumetrically, this grain structure constitutes a very small fraction of the overall part volume, the majority of the microstructure being dendritic in nature. The microstructure affects properties such as the hardness, ductility, and strength. A fully equiaxed microstructure may be achieved through recrystallization.

## 7.2 Challenges in Thermal Post-processing:

**7.2.1** The type of heat treatment process and their cycle properties depend on the material and should be performed as recommended in the corresponding standard for each material. Materials will react differently depending on their as-built condition and so the standards should only be used as a guide. Heat treatment can change the microstructure of PBF-LB built materials and so the designer should consider what microstructure is required to achieve the desired end-item properties. Consideration of the sequence of thermal processing is also important, to avoid part distortion or fusing, or both, of any residual powder. Every effort should be made to remove loose powder prior to stress relief. The challenges to be considered before performing thermal post-processing are summarized as follows.

### 7.2.1.1 Part Quality:

(1) If the quality of the inert atmosphere is poor, or unknown, oxidation may occur. High temperatures increase the rate of reaction of materials with environmental gases and contaminants. The engineer should ensure good cleanliness of parts and the furnace and sharing heat cycles with unclean parts should be avoided. Consider wrapping the parts and build platform in a sacrificial material with a high oxygen affinity.

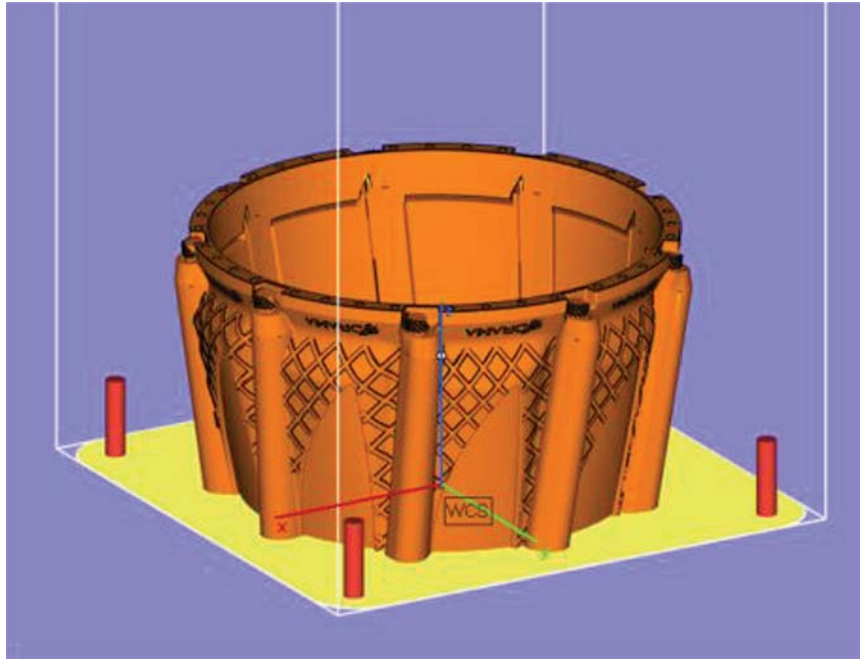


**FIG. 3 Original Design Part Oriented on Build Platform. Orientation may require the build platform to be tilted to remove powder. (Copyright MTC, all rights reserved. DRAMA was funded by UK Research and Innovation through the Industrial Strategy Challenge Fund and supported by the Aerospace Technology Institute)**

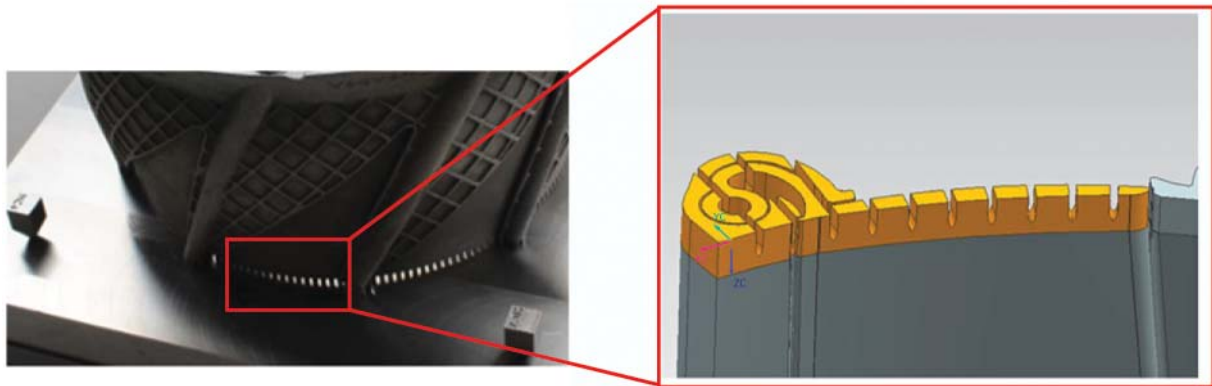


**FIG. 4 Redesigned Part with Slots Added to the Part where it Meets the Build Platform for Powder Removal. The stock section (orange) is intended to be removed by wire EDM after the build. (Copyright MTC, all rights reserved. DRAMA was funded by UK Research and Innovation through the Industrial Strategy Challenge Fund and supported by the Aerospace Technology Institute)**

than the part itself (stainless steel foil type 321, for example), to shield the previously exposed surfaces from possible oxidation. Do not puncture the foil, aim for a close fit, but not gas-tight; see Fig. 7. Decoy parts may also be placed into the furnace to absorb volatile contaminants (oxygen, moisture, carbon, nitrogen, etc.) before the component does. Gravity acts on softened material during high-temperature processing and may result in sagging if overhangs are un-supported.

(2) For materials highly sensitive to oxidation, it may be desired to perform thermal post-processing under vacuum, along with a foil wrap. Oxidation resistant alloys (Ni-base alloys for example) are heat treated in air and so the component material must be considered when selecting the most appropriate heat treat parameters.

(3) Highly pressurized inert gas expands with high temperature and so internal gas pores may re-open during HIP. Although rare, gas porosity can act as a stress site post-HIP. To minimize this, avoid high temperature processes post-HIP if possible and avoid high-temperatures in service. HIP is generally used to improve part density and improve fatigue life by minimizing pores.

(4) While selecting suppliers, a series of accreditations and standards will be stated as a representation of the quality and repeatability of their services. Table X1.1 provides descriptions of some of the most common examples.

**7.2.1.2 Surface Defects**—It is recommended to HIP prior to any machining because HIP will not close surface-connected pores. Cracks on the surface offer a way for air to infiltrate the

TABLE 2 Design Considerations Checklist

| Design Consideration            | Description                                                                                                                                                                                                                                                                                                                                         |
|---------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hollow sections                 | Access into hollow spaces inside a part to ensure all loose powder can be successfully removed is crucial. The holes/slots could be sealed later by a weld or epoxy if required.                                                                                                                                                                    |
| Large sections enclosing powder | Powder removal features could be added into the design; these can be incorporated to the stock material connecting the assembly to the build platform as shown in Fig. 4. This will allow powder removal without tilting the entire build.                                                                                                          |
| Enclosed volumes consideration  | Parts should be designed and oriented on the build platform in such a manner that powder can be removed from any enclosed volume. Powder should not be present in further post-process operations such as thermal post-processing or build platform removal.                                                                                        |
| Internal channels/cavities      | The length and the cross-section of any internal channels and cavities should be considered during design for ease in powder removal. Larger radii can be used for internal features instead of corners. Cavities with line of sight can easily be accessed and cleared of powder by compressed air, blasting media, or other methods such as wire. |
| Support structures              | Where possible, support structures should be avoided to reduce the risk of trapped powder.                                                                                                                                                                                                                                                          |

TABLE 3 Summary of Thermal Processes and their Purpose for AM Components

|                                         |                                                                                                                                                            |
|-----------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Stress relief                           | Minimizes or eliminates build induced residual stress to nucleate grains in a stress-free condition.                                                       |
| HIP                                     | Can close out internal porosity if not connected to the surface.                                                                                           |
| Homogenization, solution treatment, age | Modify the microstructure in the case of solid-solution strengthened alloys or nucleate and grow precipitates to obtain the desired mechanical properties. |

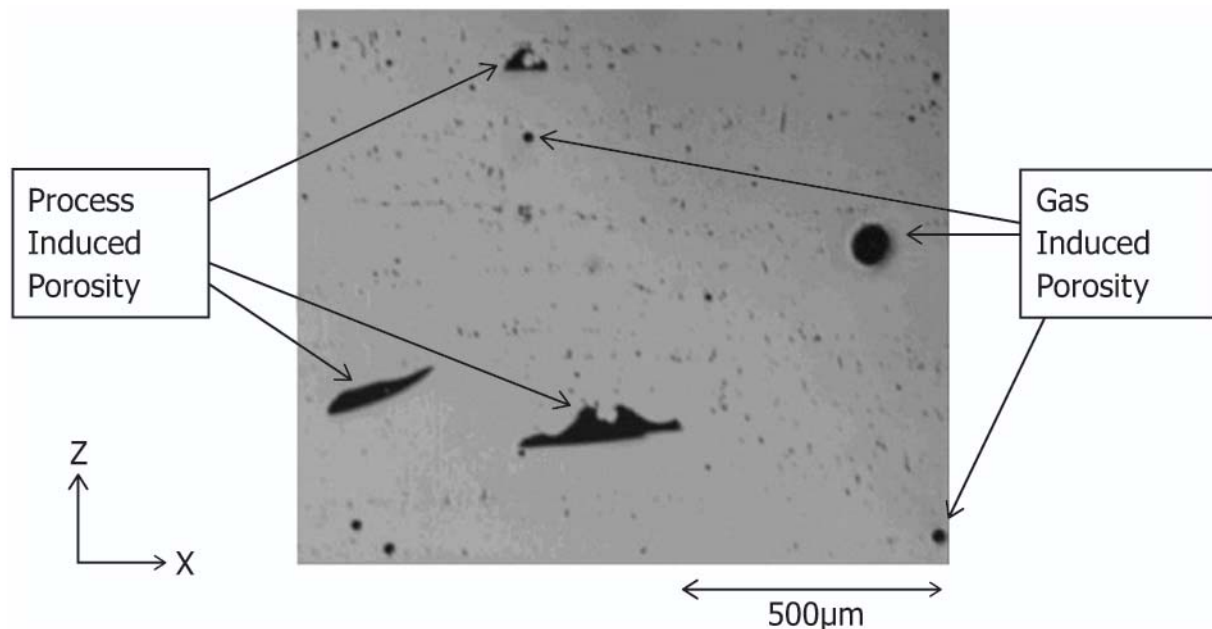


FIG. 5 Micrograph Indicating Porosity and Lack of Fusion Observe in an AM Sample (2)

part during high temperature post-processing. This can be avoided by performing a vacuum furnace evacuation followed by inert gas backfill.

**7.2.1.3 Accuracy**—Uneven thermal gradients and furnace cooling rates result in loss of geometric conformity causing distortion. Distortion control is improved by specifying furnace ramp and cool rates in a heat treatment specification. In situations where precision is paramount, enquire about the equipment's temperature uniformity volume and keep the part

within that area. Direction of quenching should be performed along the largest part axis to avoid distortion during liquid quench.

**7.2.1.4 Operation Sequence**—In order to minimize component distortion, it is recommended to perform thermal post-processing before the part removal from the build platform. The cycles used and their order is material and process dependent and so the recommendations in the relevant standard should be observed. Gas pores which are close to the surface

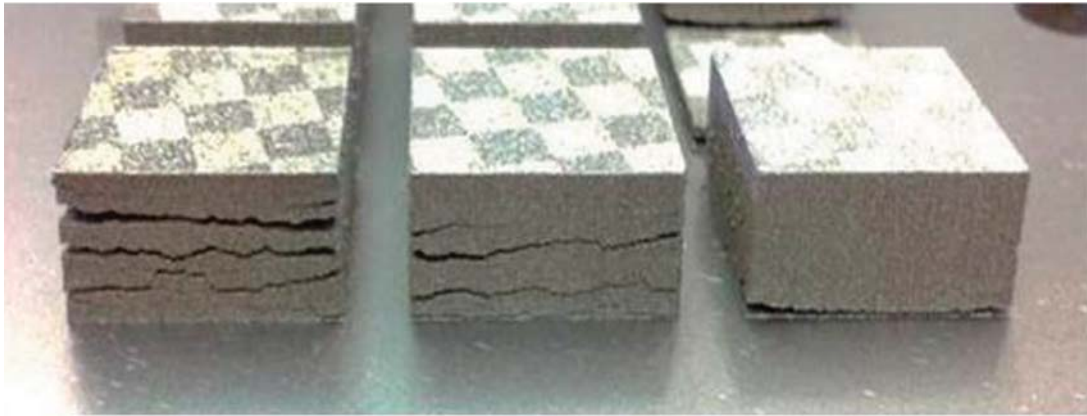


FIG. 6 Delamination and Cracking in PBF-LB Sample (3)

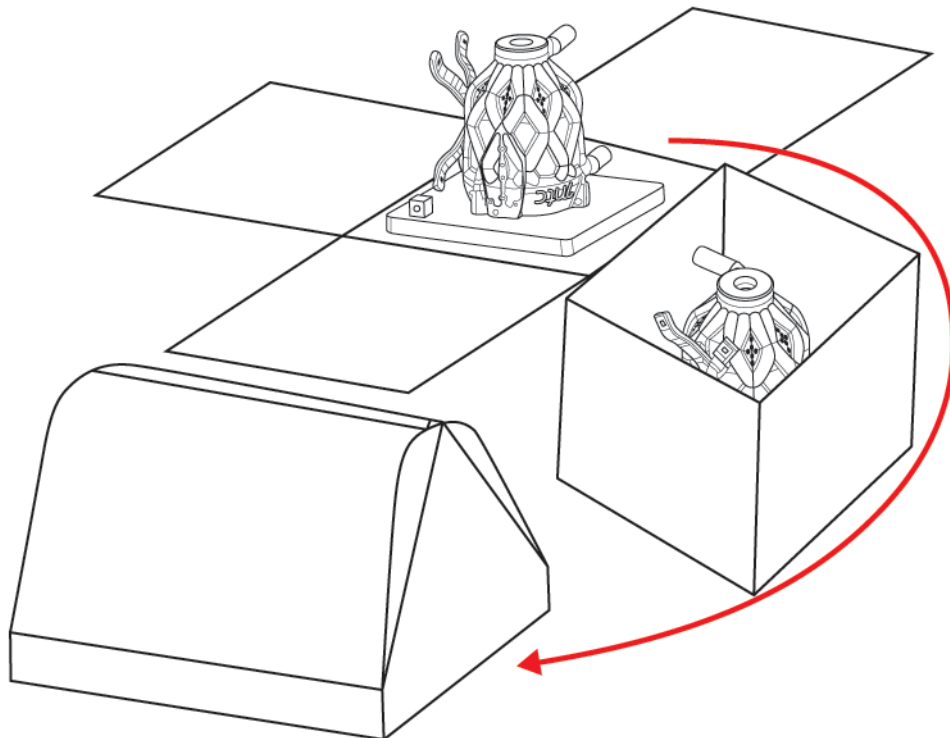


FIG. 7 Wrapping of Parts in a Box (Copyright MTC, all rights reserved)

re-open during subsequent heat treatments, high temperature cycles may also alter the microstructure and effects of subsequent treatments and so the sequence of cycles should be carefully considered.

#### 7.2.1.5 Part Handling:

(1) Contamination from touching the part prior to heat treatment may impact the material properties. The part should be handled by the build platform where possible.

(2) For components above the safe manual handling limit lifting features will need to be incorporated into the design for safe loading and unloading.

#### 7.2.1.6 Cost:

(1) Selecting the appropriate thermal post-processing cycle needs to balance the benefits gained from a dedicated HIP cycle against the potential reduction in cost from using a standard “coach” heat treatment cycle (coach cycle generally refers to consolidation of different lots from different customers together in one HIP cycle).

(2) A shared thermal cycle is regularly the most cost effective option. If a dedicated cycle is required, the cost per cycle will increase.

7.2.1.7 Lead Time—Thermal post-processing is a multistage process which increases lead-time. The time required for thermal post-processing is component (geometry, material,

end-use) dependent. If no lead time improvement over traditional manufacturing is to be achieved, it should be considered if the design improvements of AM are worth it over cast or forged components.

### 7.3 *Mitigating Thermal Post-Processing Challenges by Design:*

7.3.1 As HIPing is unable to close surface connected defects, the designer may wish to add extra material for removal to account for this as well.

7.3.2 Depending on the material, particular heat treatment equipment may be required and the size of the equipment should be considered early on in the design stage. There needs to be adequate space around the component in the furnace and parts need to be loaded according to the furnace manufacturer's guidelines.

7.3.3 Thermal treatment providers will use thermocouples to monitor the temperature profiles of the components going through a cycle. Best position for a thermocouple placement on a component should be considered; this typically corresponds to the thickest wall sections.

7.3.4 Leftover, entrapped metal powder in components might become an issue during thermal processing, as it can consolidate in undesirable places. This could happen in features such as internal channels, or cavities during a HIP cycle.

7.3.5 Part distortion may occur during thermal post-processing. To minimize any such adverse effects, factors such as part orientation and how the part will be supported in the furnace must be considered.

### 7.4 *Design for Thermal Post-Processing Checklist:*

7.4.1 The guidelines in **Table 4** are intended to help design-

ers understand the impact of thermal post-processing on part performance/quality and highlight the considerations before performing thermal post-processing. The following guidelines are advisory only.

## 8. Build Platform Removal

8.1 Metal AM components are essentially welded to the build platform in metal PBF-LB and therefore require removal prior to certain post-processing steps. It should be noted that in some cases it is beneficial to post process parts on the build platform, for example, machining. The most common processes for removing the build platform are: wire EDM, band saw, and manual removal.

8.2 The selection of the method depends on the availability of the process for the size of the components, as well as:

8.2.1 *Complexity*—Wire EDM provides the capability to remove parts and supports with a complex profile, while parts with a small surface area of contact with the build platform can be removed manually.

8.2.2 *Time Versus Quality and Cost*—Wire EDM is a slower process than band saw, but the surface quality and cost of the build platform removal is higher.

### 8.3 *Mitigating Wire EDM Build Platform Removal Challenges by Design:*

8.3.1 It is a relatively slow process.

8.3.1.1 Reducing the volume of material to cut through will also reduce the processing time. Choosing different materials and process parameters for wire EDM may also reduce the processing time.

**TABLE 4 Design Considerations Checklist for Performing Thermal Post-Processing**

| Design Consideration   | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
|------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Stock material         | Parts may distort with thermal post-processing and may go out of the required tolerance. Stock material can be added to the areas prone to distortion and can then be machined to the required accuracy. Suitable simulation approaches may be utilized to predict the amount of distortion.                                                                                                                                                                                                            |
| Material properties    | Thermal post-processing may affect the mechanical properties of materials and therefore should be accounted for during the design stage. The composition will affect how the material responds to the whole AM process. Phase diagrams and cooling curves for each material should be consulted for indications of material properties expected after thermal post-processing.                                                                                                                          |
| Thin-walled parts      | Thin-walled parts may distort during thermal post-processing and will need careful consideration. Distortion may be avoided by thickening sections and adding ribbing for instance. Suitable simulation approaches may be utilized to predict the amount of distortion.                                                                                                                                                                                                                                 |
| Temperature monitoring | Best position for a thermocouple placement on a component should be considered. This consideration may include adding features in the design to accommodate a thermocouple or a sacrificial anchoring location alongside the build. <b>Fig. 8</b> shows possible thermocouple placement locations with their expected outcome.                                                                                                                                                                          |
| Trapped powder         | Features should be added to the design to allow ease in powder removal as unwanted powder can consolidate in internal cavities.                                                                                                                                                                                                                                                                                                                                                                         |
| Supports               | To minimize part distortion during thermal post-processing, factors such as part orientation and how the part will be supported in the furnace must be considered.                                                                                                                                                                                                                                                                                                                                      |
| Build platform         | The build platform offers support to the part, preventing distortion and allowing easier handling. Therefore, it should remain attached until after thermal post-processing. If components on a build platform require different heat treatments, the build plan should be designed to allow the build platform to be carefully sectioned, leaving the parts attached. If the build platform is a different alloy than the parts, parts removal prior to post-build thermal processing may be required. |

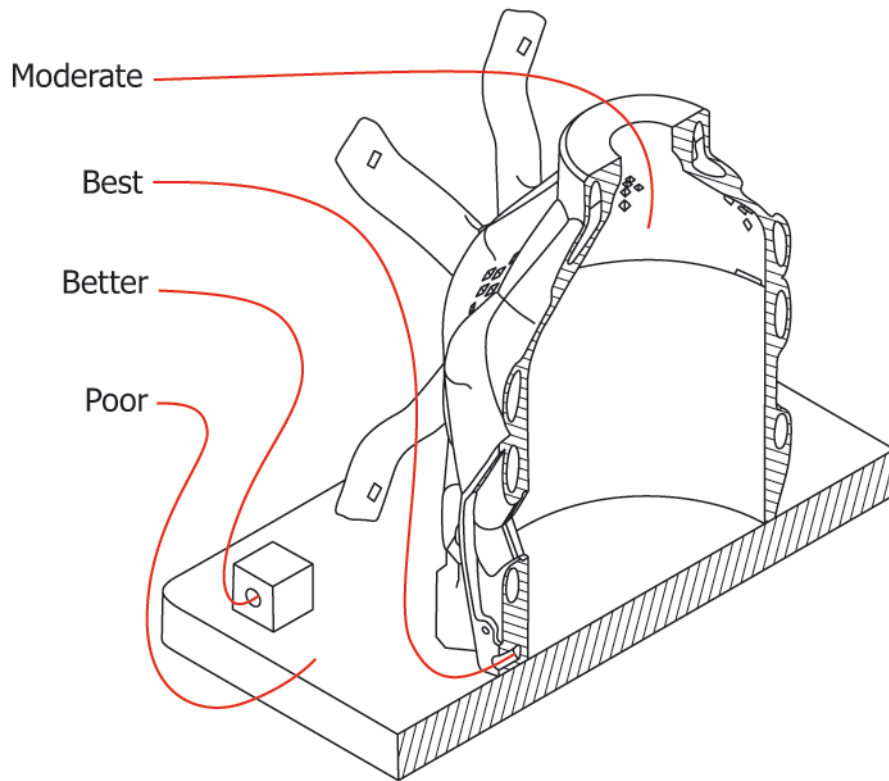


FIG. 8 Temperature Monitoring—Possible Thermocouple Locations (Copyright MTC, all rights reserved)

8.3.2 It can take a number of passes to obtain a high quality finish, although a single pass may be acceptable.

8.3.2.1 Consider the boundaries for tolerances and surface finish requirements to identify whether multiple passes are acceptable.

8.3.3 Multiple passes will require additional workholding features on the component so that it can be held in the Wire EDM machine once the build platform has been cut off.

8.3.3.1 The build platform is usually held in the wire EDM process and therefore once removed, additional workholding fixtures will need to have been designed into the component to allow it to be re-fixtured. These may incorporate tabs or blocks which can be removed in a downstream process such as machining.

8.3.4 Wire EDM settings are critical to preventing wire breakages. Contact between the wire and the part can occur if cutting too fast, leading to increased tensile stresses on the wire, potentially causing it to break.

8.3.4.1 Reducing thick to thin transitions will optimize the speed of the machine.

8.3.5 Any remaining unused powder can clog or interfere with the wire.

8.3.5.1 Enclosed volumes should not be present in the design and the addition of supports should not create enclosed volumes between the part and the build platform.

8.3.5.2 Powder can become trapped in sharp corners, in thin channels or in areas not in line of sight. Removing or reducing the number of these features will help with powder removal.

8.3.6 Parts cut free from the build platform can interfere with the wire and cause it to break.

8.3.6.1 Once cut, the parts should fall away from the wire. Parts enclosed in others can be secured to other components to prevent them from rattling around and contacting the wire.

8.3.7 Large parts can cause the build platform to distort which may lead to the cut being out of tolerance or the wire colliding with the build platform.

8.3.7.1 Additional stock material can be added between the part and the build platform to compensate for deformation of the build platform.

#### 8.4 Mitigating Band Saw Removal Challenges by Design:

8.4.1 Unable to produce a high quality surface texture.

8.4.1.1 Using large amounts of stock (generally around 5 mm) allows for the part to be further processed by another post-processing technique to provide a higher quality surface texture.

8.4.2 It is a low tolerance process and therefore typically requires a secondary process to clean up the cut surface.

8.4.2.1 Using large amounts of stock (generally around 5 mm) allows for the part to be further processed by another post-processing technique to provide a tighter tolerance and accuracy.

8.4.3 Build platforms can be easily damaged and may require repair or replacement.

8.4.3.1 Similar to the previous challenges, adding stock to the part will also help to prevent the blade catching the build platform.

8.4.4 Parts cut free from the build platform can catch on the blade.

8.4.4.1 Once cut, the parts should fall away from the blade. Parts enclosed in other over-arching parts on the build platform can be secured to other components if possible to prevent them from rattling around and contacting the blade.

#### 8.5 Mitigating Manual Build Platform Removal Challenges by Design:

8.5.1 Only works with support structures and not stock material.

8.5.1.1 Appropriate support material can be used to separate the parts and the build platform, block or solid supports removal may not be possible manually.

8.5.2 Dangers of contacting parts which could damage them.

8.5.2.1 Allow enough access for the hammer and chisel to access all areas of support material to the build platform.

8.5.3 Witness marks will be left on the parts and the build platform from the support structure. This will require additional post-processing techniques.

8.5.3.1 Prevent or remove the need to support structure in areas where tool access is difficult for manual clean up or machining.

#### 8.6 Design for Build Platform Removal Checklist—See Table 5.

## 9. Support Removal

### 9.1 Background

9.1.1 In PBF-LB, support structures are used for the following purposes:

9.1.1.1 To conduct heat from the melted layers to the build platform to reduce residual stresses.

9.1.1.2 To improve part quality by supporting overhanging features.

9.1.1.3 To anchor the part to the build platform and reduce distortion.

9.1.2 Supports are usually needed on overhanging features (generally with angle lower than 45° to the build platform) and on the base of a part to attach the lowest point to the build platform. If no other supports are needed (that is, no other downskins less than 45° from the build platform are present) and the design can be built from this point upwards, it can be defined as ‘self-supporting’. Further general design guidance could be found in ISO/ASTM 52911-1).

### 9.2 Challenges in Removing Supports:

9.2.1 Hand removal of supports usually leaves witness marks on the part where the support teeth had been attached. These have to be smoothed manually or by machining, media blasting or mechanically finishing these surfaces. Support usage should be minimized while ensuring the part is properly supported.

### 9.3 Mitigating Support Removal Challenges by Design:

9.3.1 Table 6 displays a list of considerations to take into account when adding supports and offers suggestions for how to best adjust a design for support removal.

9.3.2 An example of redesigning a part to make it self-supporting can be seen in Fig. 10. The overhang has been adjusted with a structural transition with an angle greater than

TABLE 5 Design Considerations Checklist

| Design Consideration   | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
|------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Stock material         | Stock material should be added underneath the parts touching the build platform. Wire EDM is relatively accurate and may only require 1.5 mm (or less) stock, whereas with the band saw, it is recommended to add at least 5 mm depending on part design. Large parts have the potential to distort the build platform and therefore the accuracy of build platform removal is reduced. Large parts should have greater stock added to the build platform to help compensate for any potential warping.                                                                                                  |
| Wire EDM consideration | Parts should be designed and oriented on the build platform in such a manner that any enclosed volumes with trapped loose powder do not come into contact with the wire during build platform removal to avoid loose powder exposure to the dielectric fluid in which the part is processed. The EDM cutting profile could also be used to define the geometry of the finished part as shown in Fig. 9.                                                                                                                                                                                                  |
| Support structures     | Where possible, appropriate support structures should be selected to reduce the risk of trapped powder. If wire cutting is used to cut hollow supports, there may be loose powder trapped inside. This could cause health and safety issues with the EDM operatives. It may be safer to use solid extrusions to attach the part to the build platform and wire cut through the solid bulk. Consider using perforated supports to remove the majority of powder from supports prior to post-processing. Support removal should be considered after stress relief cycle to avoid possible part distortion. |
| Manual removal         | Parts can be chiselled from the build platform and support removed by hand, using pliers and other hand tools, or crushed in a vice which can loosen the teeth attachment to the part. Manual removal is sometimes the only way small, intricate parts with support can be removed.                                                                                                                                                                                                                                                                                                                      |
| Part orientation       | Parts should be oriented in such a manner on the build platform that minimizes the need for support structures while allowing appropriate anchorage for heat dissipation and support to the down-facing surfaces. Fewer support structures could reduce the build platform removal time and lower the overall cost of production.                                                                                                                                                                                                                                                                        |

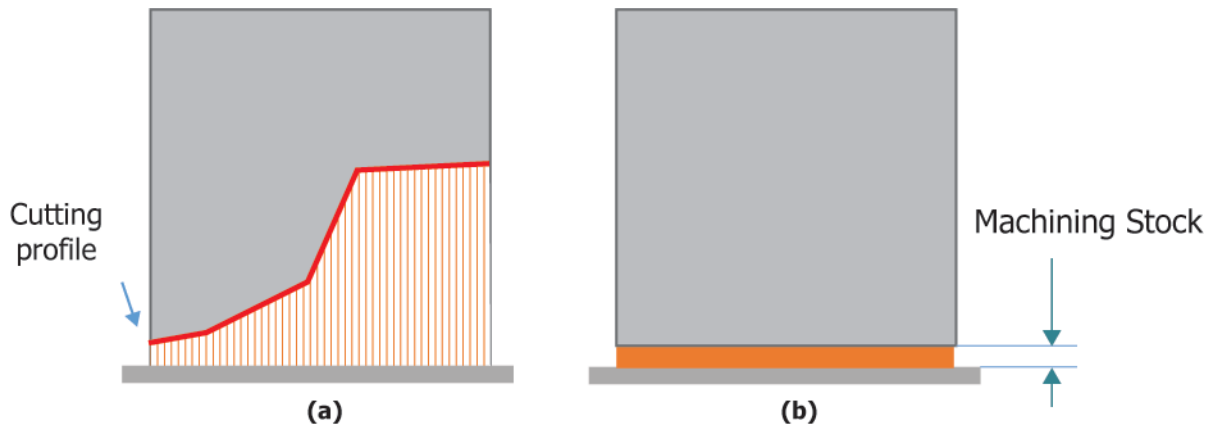


FIG. 9 Build Platform Removal—(a) Wire EDM, (b) Machining Stock (Copyright MTC, all rights reserved)

45° to the build platform, reducing the support structures required. Note that this has the side effect of increasing the material needed for the part. This might be an issue if the added weight negatively affects part performance.

9.3.3 Internal channels can have their cross-section modified to make them self-supporting. Common cross-sections used are oval, diamond or teardrop shapes. If holes need to be machined, a symmetric feature such as a diamond shape should be selected. This ensures there are equal machining forces on each side that prevent the tool from wandering. More information on machining holes can be found in 10.4.2.4.

9.4 Design for Support Removal Checklist—See Table 7.

## 10. Machining

10.1 To receive the full benefits of AM, parts should be designed in a way that requires minimal machining. The whole AM process chain needs to be considered at the design stage to prevent complications in the manufacturing stages. Machining cannot be an afterthought.

### 10.2 Background:

10.2.1 AM produces near net-shape components and a subsequent processing step is often required to bring all or some of the features to a net-shape condition. This additional processing step is usually completed by machining. Essentially, rather than design for “AM” we usually have to design for “AM and CNC.”

10.2.2 Surface texture and hard-to-predict distortion means PBF-LB parts are often not built to the accuracy and surface finish required by an application. Because of this, features cannot be produced as-built with fine tolerances. A combination of inspection technologies and machining are needed to “find the good part” in the built component. A growing number of commercially available build simulation software does exist to be able to predict distortion and failure.

10.2.3 Machining is usually needed to produce precise round holes and smooth, flat surfaces for interfacing with other parts. Functional tolerances on surfaces can be used to determine areas that require machining. Surface machining may be necessary for fatigue or air flow requirements as well as interfaces. Depending on the functional requirements of the component, surfaces can be left in the as-built state. A

demonstrator part is shown in Fig. 14. Note that only the interfaces are machined and the rest of the part is left as-built.

### 10.3 Challenges in Machining AM Components

10.3.1 Machining of AM parts can be challenging due to a number of factors:

10.3.1.1 Part geometry is often complex and non-prismatic, meaning it has a varying cross section. This leads to a lack of stability in clamping and referencing when using conventional fixturing / clamping methods.

10.3.1.2 Distortion and vibration of the part can lead to chattering during the machining operation, leading to poor machining accuracy. Lightweighting features such as thin walls / struts are common in AM parts and especially prone to this.

10.3.1.3 Lack of suitable datum features, which causes difficulty in aligning components for machining.

10.3.1.4 Difficulty in machine tool access.

10.3.1.5 Parts often have a fine grained microstructure which can lead to high level tool wear.

10.3.2 These factors make the choice of machining setup (including machine allowance), tool selection and fixturing critically important. In some cases, it may be possible to machine the component while the component is still attached to the build platform; however, this requires appropriate considerations and planning when choosing the build setup.

10.3.3 Communication is vital between design engineer, manufacturing engineer, machinist, and inspection engineer. These factors should be considered early in the design stage to avoid scrap parts and reduce the overall labor and machining cost of the product.

### 10.3.4 Requirement of a Datum System:

10.3.4.1 Datums are required to provide a frame of reference for features and characteristics on a product – part or assembly. For manufacturing, the datum system allows a link to be made between the part design and the coordinate system of the manufacturing process. In inspection, the datum system enables the inspection engineer to make this link to the measurement system, and properly evaluate characteristics as specified by design. Fixturing facilitates datuming by properly supporting parts, in an orientation that enables datum features to be accessed. Assembly datums ensure that all of the parts manufactured will fit together as intended.