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Additive manufacturing — Design —

Part 3:
PBF-EB of metallic materials

Fabrication additive — Conception —

Partie 3: PBF-EB de matériaux métalliques

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 261, *Additive manufacturing*, in cooperation with ASTM Committee F42, *Additive Manufacturing Technologies*, on the basis of a partnership agreement between ISO and ASTM International with the aim to create a common set of ISO/ASTM standards on additive manufacturing, and in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 438, *Additive manufacturing,* in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

A list of all parts in the ISO 52911 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Powder bed fusion of metals (PBF/M) is an additive manufacturing (AM) process that offers additional manufacturing options alongside other established AM processes. PBF/M has the potential to reduce manufacturing time and costs, and increase part functionality. Practitioners are aware of the strengths and weaknesses of conventional, long-established manufacturing processes, such as cutting, joining and shaping processes (e.g. by machining, welding or injection moulding), and of giving them appropriate consideration at the design stage and when selecting the manufacturing process. In the case of PBF/M and AM in general, design and manufacturing engineers only have a limited pool of experience. Without the limitations associated with conventional processes, the use of PBF/M offers designers and manufacturers a high degree of freedom and this requires an understanding about the possibilities and limitations of the process.

The ISO 52911 series provides guidance for different powder bed fusion (PBF) technologies. In addition to this document on PBF-EB/M, the series is made up of ISO 52911-1 on laser-based powder bed fusion of metals (PBF-LB/M) and ISO 52911-2 on laser-based powder bed fusion of polymers (PBF-LB/P). Each document in the series shares Clauses 1 to 5, where general information including terminology and the PBF process is provided. The subsequent clauses focus on the specific technology.

This document provides support to technology users, such as design and production engineers, when designing parts that need to be manufactured by means of PBF-EB/M. It will help practitioners to explore the benefits of PBF-EB/M and to recognize the process-related limitations when designing parts. It also builds on ISO/ASTM 52910 to extend the requirements, guidelines and recommendations for AM design to include the PBF-EB/M process.

Additive manufacturing — Design —

Part 3:
PBF-EB of metallic materials

1 Scope

This document specifies the features of electron beam powder bed fusion of metals (PBF-EB/M) and provides detailed design recommendations.

Some of the fundamental principles are also applicable to other additive manufacturing (AM) processes, provided that due consideration is given to process-specific features.

This document also provides a state of the art review of design guidelines associated with the use of powder bed fusion (PBF) by bringing together relevant knowledge about this process and by extending the scope of ISO/ASTM 52910.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/ASTM 52900, *Additive manufacturing — General principles — Fundamentals and vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/ASTM 52900 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
curl effect
<aspect of heat-induced warping> dimensional distortion as the melted material cools and solidifies after being built or by poorly evacuated heat input

3.2
downskin area
D
(sub-)area where the normal vector $\vec{n}$ projection on the Z-axis is negative

Note 1 to entry: See Figure 1.

3.3
downskin angle
δ
angle between the plane of the build platform and the *downskin area* (3.2) where the value lies between 0° (parallel to the build platform) and 90° (perpendicular to the build platform)

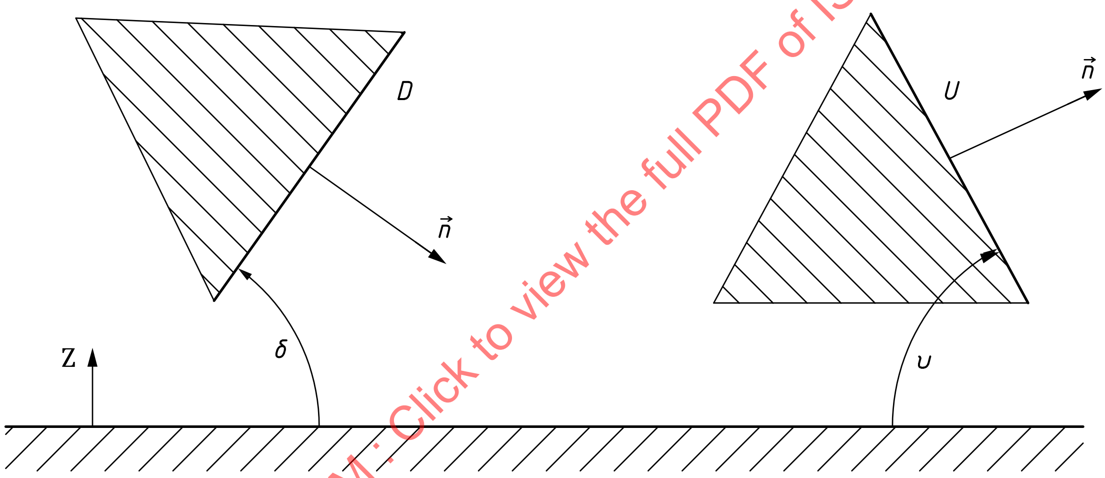
Note 1 to entry: See Figure 1.

3.4
upskin area
U
(sub-)area where the normal vector $\vec{n}$ in relation to Z-axis is positive

Note 1 to entry: See Figure 1.

3.5
upskin angle
υ
angle between the plane of the build platform and the *upskin area* (3.4) where the value lies between 0° (parallel to the build platform) and 90° (perpendicular to the build platform)

Note 1 to entry: See Figure 1.



Key

δ	downskin angles	***U***	upskin (right) areas
$\vec{n}$	normal vector	***υ***	upskin angles
D	downskin (left) areas	Z	build direction

NOTE Source: VDI 3405-3:2015[3].

Figure 1 — Orientation of the part surfaces relating to the build platform

4 Symbols and abbreviated terms

4.1 Symbols

The symbols given in Table 1 are used in this document.

Table 1 — Symbols

Symbol	Designation	Unit
a	overhang	mm

Table 1 *(continued)*

Symbol	Designation	Unit
D	downskin area	mm^2
I	island	mm^2
$\vec{n}$	normal vector	—
U	upskin area	mm^2
δ	downskin angle	°
υ	upskin angle	°

4.2 Abbreviated terms

The following abbreviated terms are used in this document.

CT computed tomography

DICOM digital imaging and communications in medicine

PBF-EB/M electron beam powder bed fusion of metals

HIP hot isostatic pressing

PBF-LB laser-based powder bed fusion

PBF-LB/M laser-based powder bed fusion of metals (also known as, for example, laser beam melting, selective laser melting)

PBF-LB/P laser-based powder bed fusion of polymers (also known as, for example, laser beam melting, selective laser melting)

MRI magnetic resonance imaging

5 Characteristics of powder bed fusion (PBF) processes

5.1 General

Consideration should be given to the specific characteristics of the manufacturing process used in order to optimize the design of a part. Examples of the features of AM processes which need to be taken into consideration during the design and process planning stages are listed in 5.2 to 5.8. With regards to metal processing, a distinction can be made between, for example, laser-based PBF (applied for metals and polymers) and electron beam-based PBF (applied for metals only).

Polymers PBF uses, in almost every case, low power lasers to sinter polymer powders together. Electron beam powder bed fusion for polymers is not usually considered because the negative charge from the electron beam will accumulate in non-conductive polymer powder and cause repulsive events that will ruin powder layer continuity and make any controlled sintering or melting impossible. As with polymer powders PBF, metals PBF includes varying processing techniques. Like polymers, metals PBF often requires the addition of support structures (see 6.3.3). Metals PBF processes may use low-power lasers to bind powder particles by only melting the surface of the powder particles or high-power (approximately 200 W to 1 kW) energy beams to fully melt and fuse the powder particles together.

PBF-EB/M and PBF-LB/M have similar capabilities, although differences between these processes leads, in general, to PBF-EB/M supporting faster build rates at lower feature resolution compared to PBF-LB/M. The beam energy from the electron beam is of a higher intensity (due to a high energy source 3 kW to 6 kW), and the mechanism to raster the beam (i.e. electromagnetics for PBF-EB/M, optics for PBF-LB/M) differs between the two types of PBF processes. PBF-EB/M also tends to utilize a larger beam spot size, larger powder size distribution, and larger layer thickness. In general, PBF-EB/M subjects parts to less thermal stresses (as powder layers are preheated before melting) and have faster build rates, but the trade-off often comes with general greater minimum feature sizes and greater surface roughness compared to PBF-LB/M.

5.2 Part size and cost considerations

Part size is not only limited by the working area/working volume of the PBF-machine. The occurrence of cracks and deformation due to residual stresses can also limit the maximum part size. Another important practical factor that can limit the maximum part size is part cost having a direct relation to part size.

Part cost can be minimized by choosing part location and build orientation in a way that allows nesting of as many parts as possible.

Also, powder reuse protocols impact part cost significantly. If no reuse is allowed then all remaining powder is scrapped regardless of volume solidified.

5.3 Benefits to be considered in regard to the PBF process

PBF processes can be advantageous for manufacturing parts where the following points are relevant:

- Integration of multiple functions in the same part.
- Parts can be manufactured to near-net shape (i.e. close to the finished shape and size).
- Degrees of design freedom for parts are typically higher. Limitations of conventional manufacturing processes do not usually exist, e.g. for
  - tool accessibility, and
  - machining undercuts.
- A wide range of complex geometries can be produced, such as
  - free-form geometries, e.g. organic structures,
  - topologically optimised structures, in order to reduce mass and optimize mechanical properties,
  - infill structures, e.g. honeycomb, and
  - porous lattice structure on surface of otherwise solid component, e.g. osteosynthesis structures in medical device industry.
- The degree of part complexity is largely unrelated to production costs, unlike most conventional manufacturing.
- Assembly and joining processes can be reduced through part consolidation, potentially achieving in bloc construction.
- Overall part characteristics can be selectively configured by adjusting process parameters locally.
- Reduction in lead times from design to part production.

5.4 Limitations to be considered in regard to the PBF process

Certain disadvantages typically associated with AM processes should be taken into consideration during product design:

- Shrinkage, residual stress and deformation can occur due to temperature differences. Preheating of the powder bed (which is the normal procedure in PBF-EB/M) can be used to minimize these effects.

- The surface quality of AM parts is typically influenced by the layer-wise build-up technique (stair-step effect) and utilized powder size distribution. Post-processing may be required, depending on the application.
- Consideration should be given to deviations from form, dimensional and positional tolerances of parts. A machining allowance should therefore be provided for post-production finishing. Specified geometric tolerances can be achieved by precision post-processing operations.
- Anisotropic characteristics typically arise due to the layer-wise build-up and should be taken into account during process planning.
- Not all materials available for conventional processes are currently suitable for PBF processes.
- Material properties can differ from expected values known from other technologies like forging and casting. Material properties can be influenced significantly due to process settings and control.
- Excessive use and/or over-reliance on support structures can lead to both high material waste and increased risk of build failure.
- Unmelted powder removal after processing is necessary. For PBF-EB/M this powder is often lightly sintered instead of loose due to powder bed preheating during processing.

5.5 Build layout, part orientation, and cost considerations

Provided that the geometry permits a part to be placed in the build space in such a way that it can be manufactured as cost-effectively as possible, various criteria for optimization are available depending on the number of units planned.

- Build height is a factor that has significant impact on building time and build costs. Parts should be oriented in such a way that the build height is kept to a minimum. However, additional and sometimes competing factors should also be considered when deciding on part orientation. Simplifying post-processing operations such as powder and support removal, as well as ensuring features that are critical to the function of the part building appropriately are two such additional considerations.
- If the intention is to manufacture a larger number of units, then the build space should be used as efficiently as possible. Parts should be oriented so as to minimize the number of build runs required. Strategies for three-dimensional nesting can also be included to maximize the available build volume.
- If the same parts are oriented differently for best packing, i.e. results in building at different angles, then the mechanical properties can vary from part to part.
- The use of powder that remains in the system depends on the application, material and specific requirements. Powder changes can be inefficient and time consuming. Though they are necessary when changing material type, powders from same-material builds can be reused if permitted in the governing specification. It is important to note, however, that powder reuse can affect the powder size distribution, surface characteristics and alloy composition, and this will in turn affect final part characteristics. In addition, the reusable powder characteristics may be different for PBF-EB/M and PBF-LB/M. The number of times a powder can be recycled is dependent on the requirements outlined in the material and part specifications, and the powder reuse scheme implemented by the user and machine manufacturer.
- Many poorly designed parts (particularly those designed for conventional processes with little or no adaptation) necessitate a specific orientation either to minimize the use of supports or to increase the likelihood of build success. Indeed, parts designed for additive manufacture should be devised such that build orientation is obvious and/or specified.

5.6 Feature constraints (islands, overhang, stair-step effect)

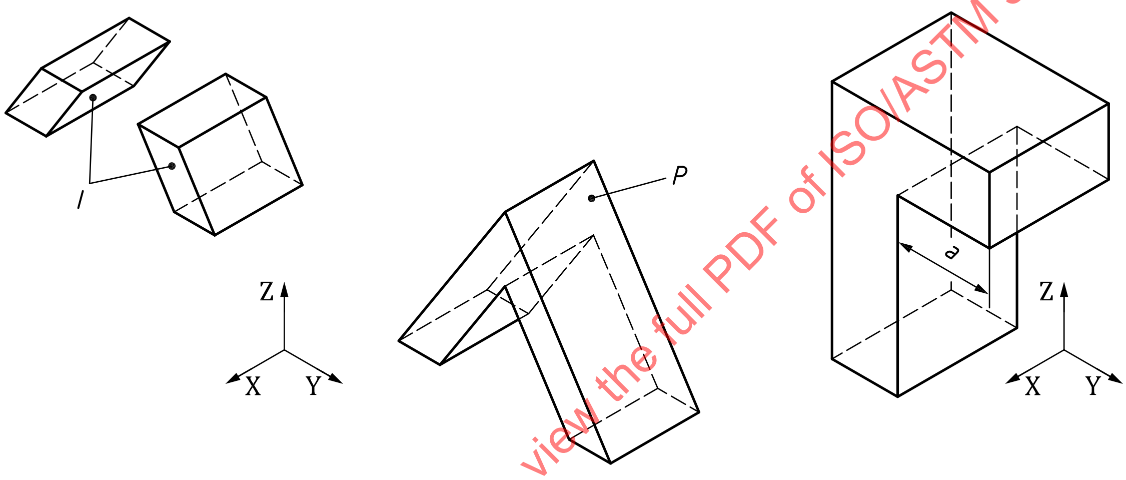
5.6.1 General

Since AM parts are built up in successive layers, separation of features may occur at some stage of the build. This depends on the part geometry. The situations described in 5.6.2 to 5.6.4 can be regarded as critical (the level of criticality depends on the PBF technology in focus) in this respect.

5.6.2 Islands

Islands, *I*, are features that connect to form a part, *P*, only at a later stage of the build process. How these connections occur should be taken into consideration at the design stage. Parts that are stable in terms of their overall design can be unstable during the build process (see Figure 2, left and centre).

NOTE In some circumstances, islands are not protected against mechanical damage during the powder application process. This can lead to deformation of the islands.



Key

I islands

P part

a overhang

Z build direction

NOTE 1 Overhang *a* illustrated in separate part (right).

NOTE 2 Source: VDI 3405-3:2015[3].

Figure 2 — Islands *I* (left) during the construction of part *P* (centre)

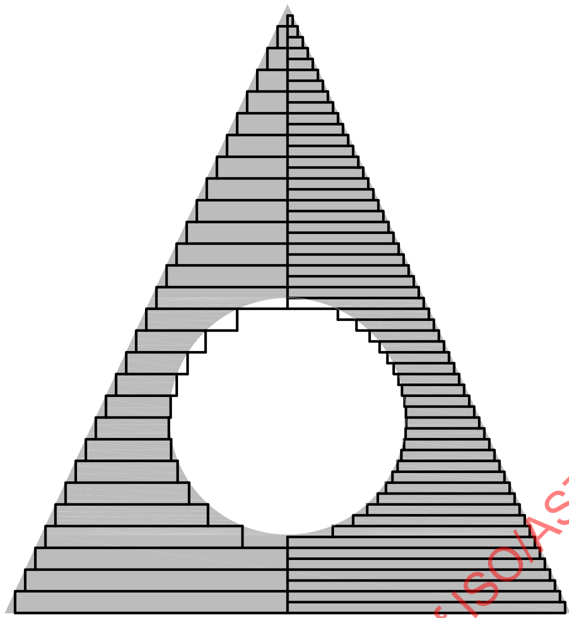
5.6.3 Overhang

Areas with an overhang angle of 0° produce an overhang with length *a* (see Figure 2, right). Small overhangs do not need any additional geometry in the form of support structures. In such cases, the projecting area is self-supporting during manufacturing. The permissible values for *a* will depend on the specific PBF process, the material and the process parameters used. Significant overhangs can induce a collapse or deformation of the length *a*, which can lead to the machine standstill (build crash).

5.6.4 Stair-step effect

Due to the layer-wise build-up, the 3D geometry of the part is converted into a 2.5D image before production, with discrete steps in the build direction. The resulting error caused by deviation of this

2.5D image from the original geometry is described as the stair-step effect. The extent of this is largely dependent on the layer thickness (see Figure 3).



NOTE Source: VDI 3405-3:2015[3].

Figure 3 — Impact of different layer thicknesses on the stair-step effect

5.7 Dimensional, form and positional accuracy

Typically, it is not possible to produce the tolerances that can be achieved with conventional cutting tool-based manufacturing processes. For this reason, post-processing may be necessary to meet (customer) requirements. Post-processing may include subtractive manufacturing, surface finishing, thermal processing, or other operations according to ISO/ASTM 52910[1]. Additional material may need to be added to the design to accommodate post-processing.

In this respect, it is particularly important to be aware of and consider process parameters that will influence characteristics of the final part. For example, build orientation to some extent determines the level of accuracy that can be achieved. Directionally dependent (anisotropic) shrinkage of the part can occur due to the layer-wise build-up. As another example, layer-wise consistency can be affected by the location of the part on the build platform.

5.8 Data quality, resolution, representation

The use of AM requires 3D geometric data, which is typically represented as a tessellated model, but other representations that can also be used include voxels or sliced layer representations. For tessellated data, files describe the surface geometry of a part as a series of triangular meshes. The vertices of the triangles are specified using the right-hand rule and the normal vector. Historically, the STL file format has been the most commonly used three-dimensional mesh data exchange format used in additive manufacturing. The ISO/ASTM 52915[2] standard AMF format is the preferred format for data exchange. The 3MF file format promoted by an industry consortium is also used in some additive manufacturing applications, but it is not an open standard recognized by any standards body.

In a tessellation, curved surfaces are approximated with triangles and the chosen resolution of the tessellation determines the geometric quality of the part to be fabricated. If the resolution is too low, the sides of the triangles specified in the STL file will be visible on the finished surface (i.e. it will appear faceted). However, a tessellation with a resolution that is too high requires a lot of digital storage space and is slow to transfer and handle using processing software. The resolution of a tessellation is generally influenced by a tolerance measure, often called “chord height”, which describes the maximum deviation of a point on the surface of the part from the triangle face. Therefore, smaller tolerance values lead to lower deviations from the actual part surface. A typical rule of thumb is to set the tolerance to be 5 to 10 times smaller than the resolution of the AM process. As a result, a chord height setting of 0,01 mm to 0,02 mm is recommended for most PBF processes. Other parameters can be used to set mesh accuracy, depending on the system.

AMF supports the representation of information beyond just geometry. For example, part units (millimetres, meters, inches), colours, materials and lattice structures are supported. STL files only contain the tessellated geometry, while 3MF files have some of the metadata representation capabilities of AMF. Having units incorporated into the data exchange file is very important in communicating part size. Arrays of parts can be precisely positioned relative to each other in a single AMF file by use the “constellation” element.

If part geometry was imported from a 3D imaging modality, such as CT or MRI, then the data are composed of voxels. The DICOM format is the standard used in the medical imaging industry and some AM software tools read these files directly. Geometry resolution is controlled by the imager resolution.

6 Design guidelines for electron beam powder bed fusion of metals (PBF-EB/M)

6.1 General

6.1.1 Selecting PBF-EB/M

PBF-EB/M is a process with typical advantages and disadvantages. The technology offers opportunities in complex design with integrated functions in one part, materials with internal structures, and/or features with undercuts or structures that cannot be realized by casting, forging, or metal cutting processes. The flexibility of PBF-EB/M offers opportunities for small series of unique products with properties that cannot be realized with other technologies.

The advantages that occur in the use phase is an important consideration when choosing PBF-EB/M, even when PBF-EB/M has disadvantages in the production phase.

Important constraints can be the availability of the required materials, limited size of the part, the approval of the technology in critical applications, the production costs, and the possible need for post processing treatments.

Some other technologies that could be applied in a similar field of application as PBF-EB/M are: PBF-LB/M, directed energy deposition of metals, or investment casting (lost wax casting) based upon a lost model produced by AM.

6.1.2 Design and test cycles

Part optimization can be constrained by current limits of the PBF-EB/M process. This could differ from material to material, from machine to machine and from service provider to service provider. Often this means that practical testing of part features is part of the design cycle.

6.2 Material and structural characteristics

Metals and metal alloys are the materials most commonly used for PBF-EB/M. Preferred methods of production for metal powders typically include plasma or gas atomization in an inert atmosphere. Because metal powders can vary significantly between suppliers, selection should be done with care. Powder size distribution, chemistry, surface characteristics, and morphology are just some examples of raw powder characteristics that need to be considered during selection.

The successful processing of individual materials depends on a variety of factors, such as weldability, melting temperature, thermal conductivity, melt viscosity and wetting angle (relating to the surface tension of the melt[4]). These factors will all affect the characteristics of the part being manufactured. For this reason, design for PBF-EB requires taking processing environments into consideration as well.

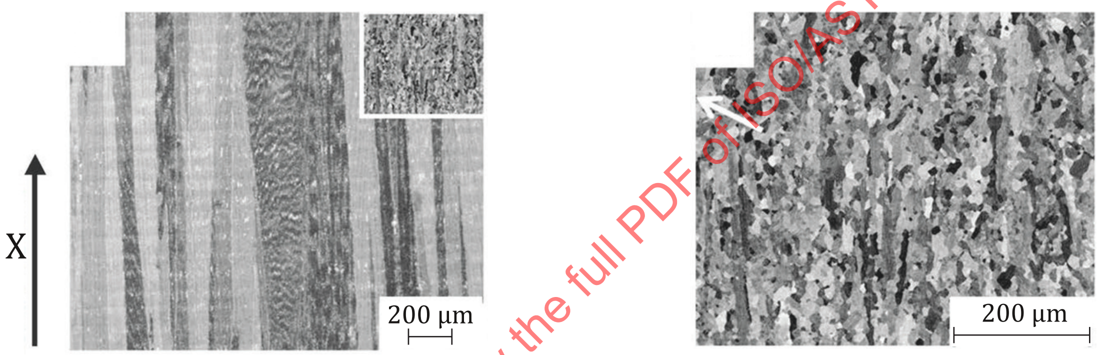
For the most current list of material classes that are available to PBF-EB/M processes, it is recommended to consult with machine and powder manufacturers. As AM technology advances, it is expected that new materials will continue to become available. As there are already metal powders available for processes like powder metallurgy, metal injection moulding and cladding, it can be expected that there is a potential for use in PBF-EB/M as well.

It is possible to achieve a relative part density close to 100 %[5].

Figure 4 depicts how small changes in PBF-EB/M processing can lead to significant differences in microstructure.

The microstructure created by the PBF-EB/M process is different from that observed in wrought materials, and is heavily dependent on the processing environment, including those factors mentioned above. The mechanical properties of the part will correlate directly with the macro- and microstructure formed.

Post heat treatments of parts produced by PBF-EB/M are applied commonly for tuning material properties.



a) Grain elongation in the build direction **b) Equiaxed grains**

Key

X build direction

NOTE Source: GE Arcam

Figure 4 — Inconel 718 Microstructures for two different PBF-EB/M processing conditions showing differences in resultant grain morphology

6.3 Build orientation, positioning and arrangement

6.3.1 General

The orientation, positioning and arrangement of parts during PBF-EB/M have an impact on process costs, process stability and various part characteristics. Factors that help to determine proper orientation, positioning and arrangement are discussed in 6.3.2 to 6.3.7.

6.3.2 Powder spreading

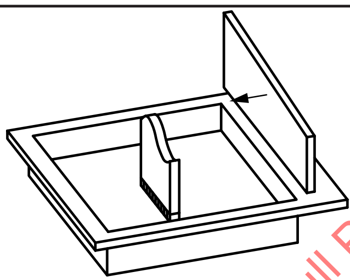
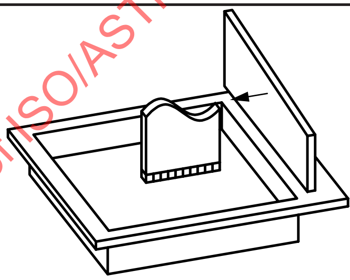
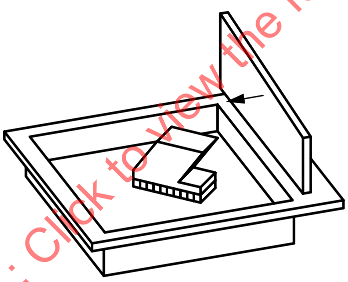
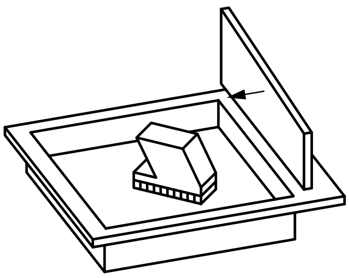
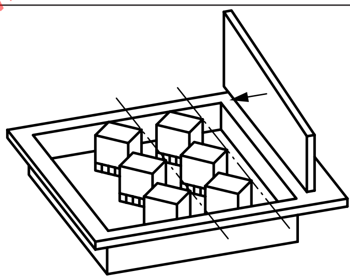
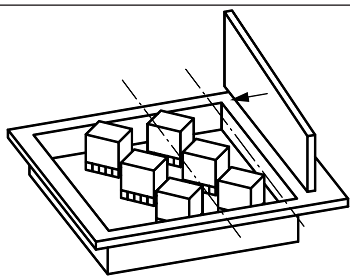
Most PBF systems use a powder layering system with a spreading device (e.g. ceramic, metal or silicon blade, or roller or carbon brush) that pushes powder from the supply chamber, across the build space, and into the powder run-off area. Depending on the layer thickness, with this type of spreading the blade often scrapes or interferes with the part as each successive layer is applied. Parts should therefore, be oriented, positioned and arranged so as to minimize the frictional forces generated during scraping. Some spreading devices (e.g. tined metal foil rakes) have been shown to be less sensitive to scraping due to reduced friction between spreading device and part. For this type of spreading device, the considerations of this section can be largely disregarded. In addition to the type of spreading device, both uni- and bi-directional spreading may be used in a given PBF system. For bi-directional spreading devices, adhering to the considerations mentioned in this section may become more difficult. Additionally, wear on the spreading device due to friction between spreading device and part can negatively affect the process (e.g. changes in powder layer thickness and continuity). The following points should be considered (see Table 2):

— longitudinal geometries should not be oriented parallel to the spreader, but rather in the spreading direction;

— wherever possible, critical geometries should not be built-up counter to the spreading direction;

— multiple parts should be positioned in a way that the contact length with the spreading system is minimized (arranged with an offset, see the last row of Table 2).

Table 2 — Arrangement of critical elements in the build space of the machine

Description	Poor	Good
Longitudinal geometries should be oriented in a way that the contact length with the spreading system is minimized.		
Critical geometries (uni-directional raking) should be oriented in a way that avoids parts being bent-up if there is a contact between spreading system and part. A suitable angle is often 10°. Gradual transitions in the XY plane and Z height have less likelihood of wiper wear and wiper related failure.		
Multiple parts should be positioned in a way that the contact length with the spreading system is minimized (arranged with an offset).		
NOTE Source: VDI 3405-3:2015[3].		

6.3.3 Support structures design

The PBF-EB/M process sometimes requires the part to be securely connected to the build plate. The connections can be made either directly (build directly on build platform) or by means of support structures. Support structures in PBF-EB/M processes serve multiple functions, including

— dissipation of heat,

— securing the part to the build platform and improving geometric accuracy,

— compensating for residual stress-induced warping, and

— as a provisional support for a piece under construction.

While support structures are common in many AM processes, specific guidance on their application is process dependent. Table 3 provides guidance on the use of support structures in PBF-EB/M processes. The values used in Table 3 are general guidelines, and both process parameters and material specifics will affect the governing values.

Because support structures are so important when designing for AM, the designer should decide at an early stage about the build orientation of the part for the particular PBF-EB/M machine and should be aware of the central elements of the process chain needed for manufacturing. The effect of the support design can therefore be taken into account when several design decisions are available. For instance, a design configuration could lead to an increase in build time but could also significantly reduce effort in post-processing to remove the support structures (see 6.8, Figures 10 and 11).

Table 3 — Guidance on the use of support structures

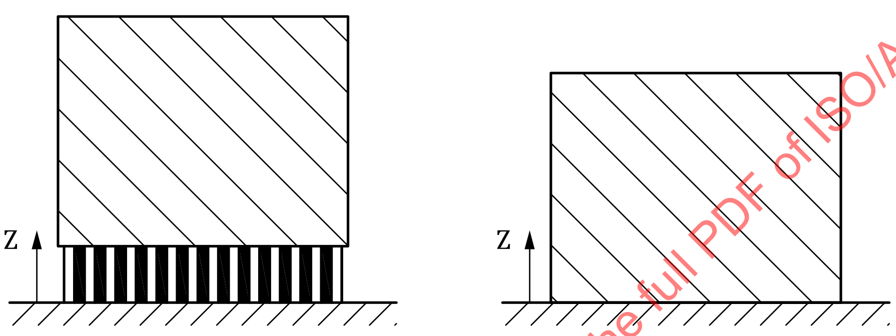
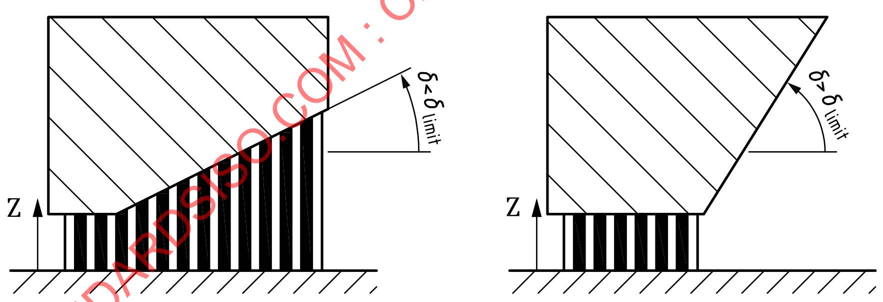
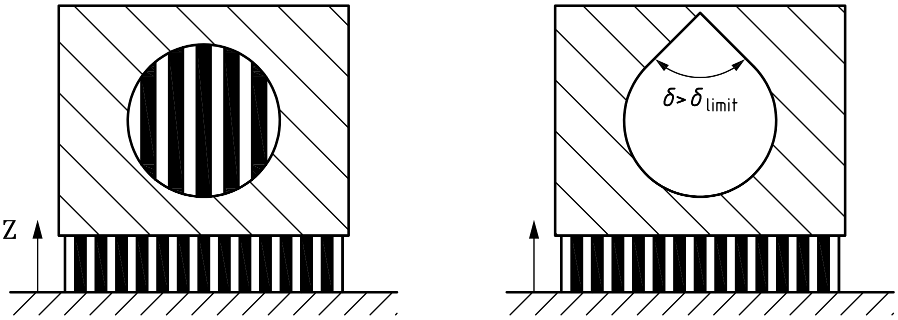
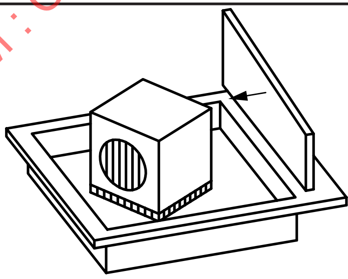
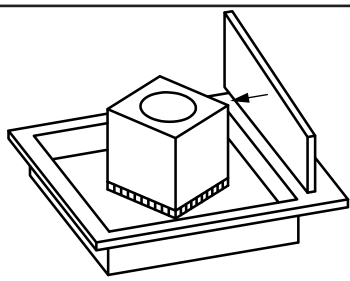
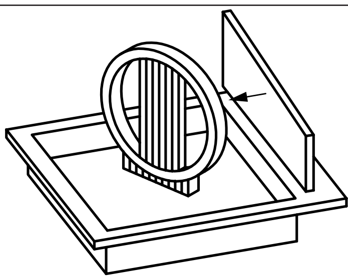
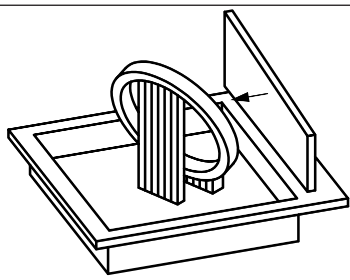
	Left: Support structures connecting the part to the build platform Right: Part connected directly to the build platform without support structures *Comment: In order to avoid the risk of cracks, a fillet can be foreseen between the part and the plate (not included in sketch).* *Comment 2: When supporting a part directly to the build substrate, removal can be complicated due to trapped powder.*
	Left: Faces with downskin angle $\delta < \delta_{\text{limit}}$ require support structures. Often, δ_{limit} is between 30° and 45°. δ_{limit} is dependent on, for example, the material used, the process strategy applied, and also the part characteristic (thickness, shape, etc.) and build characteristic (number of parts in build, etc.) above the regarded face. Because of this, the exact δ_{limit} for a given part is best determined experimentally. Right: Faces with downskin angle $\delta > \delta_{\text{limit}}$ do not require support structures. The surface quality may be adversely affected, depending on the angle.
NOTE Source: VDI 3405-3:2015[3] (except for right figure in middle row).	

Table 3 *(continued)*

	Left: Hole with internal support structure Right: Shape of hole modified to avoid use of support structures *Comment: If drilling operation is needed after PBF-EB/M, this shape is difficult to machine. Hence, in some cases, it might be better to reduce diameter of hole (often no need for support below diameter of 8 mm) in order to be built without support and drill after or even do not foresee a hole and fully drill instead (e.g. titanium).*
NOTE Source: VDI 3405-3:2015[3] (except for right figure in middle row).	

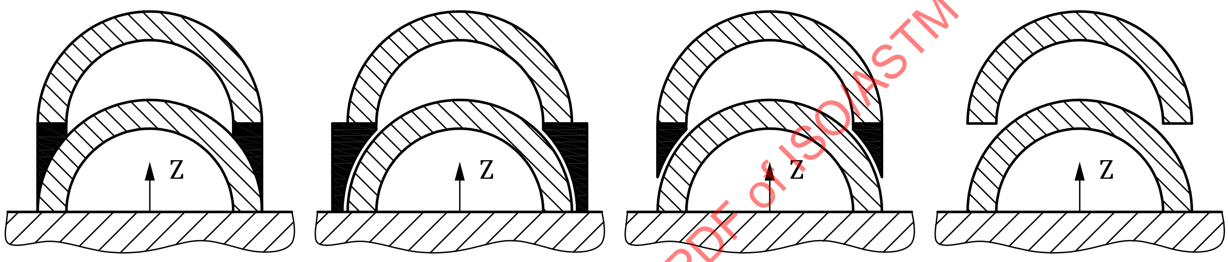
Build orientation and part shape have a significant influence on the number of support structures required. However, a balance has to be struck between support structures, efficiency, process stability and part quality. Table 4 illustrates various concepts that can aid in determining suitable process plans. In general, attention should be given to the design of the interface between support and part (punctual or line contact), with consideration of whether and, if so, how the support structures need to be removed after build-up (manually, by machining including wire electrical discharge machining etc.). Furthermore, support structure design can be realized in various shapes (e.g. block shape, web shape) and densities (e.g. gap width, web diameter). Ultimately, it is not always necessary to provide support structures between the part and the build plate. If parts exhibit rather massive areas, support structures for filigree part areas can be designed between those massive areas and the faces to be supported. Support structures can advantageously be part of the final part and not be removed at the end of building.

Table 4 — Examples of support structures

Description	Poor	Good
Avoiding support structures through part orientation that leads to least need for support structures.		
Avoiding post-processing effort through support structure design that considers the desired post process for its removal.		
NOTE Source VDI 3405-3:2015[3].		

6.3.4 Part nesting

Nesting parts provides more efficient use of the available build volume and can lead to reduced build time per part and cost per part (see 6.8, Figures 8 and 9, Tables 5 and 6). It is important to note that nesting is achieved in the Z-direction (i.e. part stacking) depending on the part geometry. Figure 5 depicts examples of support designs for stacked parts. It is possible to connect supports from higher-layer parts directly to the parts below them (Figure 5a). Keep in mind this will create additional surfaces that will require support removal (i.e. top surfaces of lower-layer parts). It is also possible to connect supports directly to the build plate (Figure 5b), but this can affect the packing efficiency of parts in the x-y plane, possibly leading to less parts fitting on each layer and reducing the overall space efficiency of the build. Due to the lower thermal stresses common to PBF-EB/M as a result of layer preheating and the resulting higher background process temperature (approximately 400 °C to 800 °C), it can be possible that higher-layer parts require no connection to any other part or the build plate. In these cases, either floating supports (Figure 5c) or no supports at all (Figure 5d) may suffice. These support designs offer advantages in build space efficiency and/or ease of support removal, but the potential for part warping and part movement leading to failure to hold desired dimensional tolerance should be carefully considered for each new part geometry/orientation. Also, for any stacking scenario, regardless of support design, the potential for higher-layer parts to have different thermal history/microstructure/mechanical properties compared to lower-layer parts should be carefully considered and investigated, if possible.



NOTE Source: National Institute of Standards and Technology.

Figure 5 — Examples of support design (solid black) for parts nested in the Z-direction (i.e. part stacking)

6.3.5 Build plate part design considerations

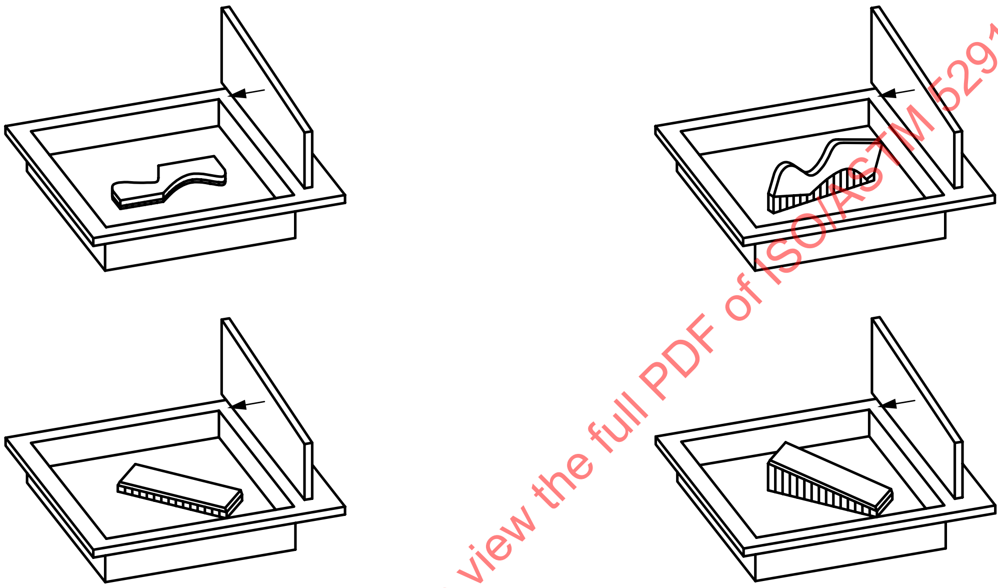
PBF-EB/M processes utilize thinner build plates that are not firmly attached to the build chamber, compared to the much thicker and firmly attached build plates used by PBF-LB/M. PBF-EB/M also can permit, for titanium only, re-using build plates without machining flat between builds. Over multiple uses, build plates develop slight dimensional variations due to warping from repeated thermal cycling and scarring from part attachments in previous builds. Part design should consider this dimensional variation in build plates. It is required that supported parts should have a support length of at least 2 mm from the build plate, and parts attached directly to the build plate should add 2 mm to any part surface attached to the build plate. This is to avoid potential diffusional zones associated with the difference in the start plate material and material being built. It is not advisable to orient parts such that areas with tight dimensional tolerance requirements are attached to the build plate.

PBF-EB/M also tends to utilize build plate materials that differ from the AM build material (e.g. stainless steel build plate for AM titanium build material). Because of this, parts tend to self-release from the build plate during cooling, due to a mismatch in thermal expansion. Advantageously, post-processing cutting is not usually necessary for part removal from the build plate.

It is also possible to include the build plate in what will eventually become the final part (e.g achieving single crystal microstructure using single crystal baseplate material). In this case, post-process operations such as machining would most likely be used to realize the final part.

6.3.6 Curl effect

Depending on the geometry of the parts being fabricated, their orientation can significantly affect the extent of the curl effect. To counter this effect, it is advisable to avoid fusing large part surfaces during a single pass wherever possible. If this cannot be accomplished by changing part orientation, there are other techniques that can be implemented to mitigate curl effect (i.e. part warping). Warping of large part surfaces can often be prevented through the use of suitably designed support structures (see Figure 6) as these supports both increase heat conduction away from the part as well as physically anchor the part to resist warping. There are also multiple heat control techniques, which minimize warping by adding heat to the overall build area in various ways. Design-based heat control techniques include simply adding more parts to the build plate to increase the overall heat of the build and reduce the potential for warping. There are also process-based heat control techniques, but the specifics of those techniques are outside the scope of this design guide. One possible way to accomplish increased powder layer preheating is to fill the build plate with replicate parts or parts with the same height. If this is not an option, low-volume parts can be added toward the corners of the build plate to force an increase in the size of the preheating area and maximize background heating.



a) Poor

b) Good

NOTE Source VDI 3405-3:2015[3].

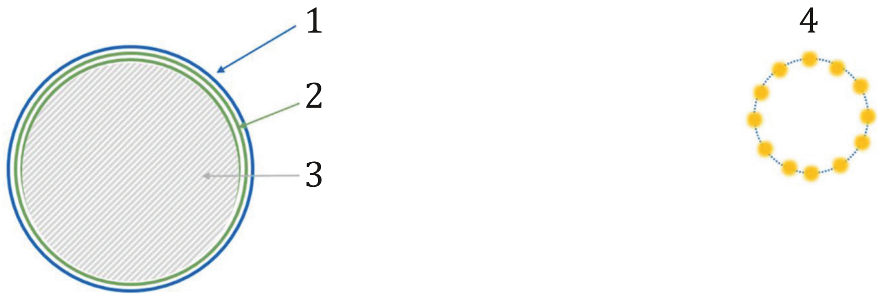
Figure 6 — Examples showing how to avoid the curl effect when irradiating large surfaces

6.3.7 Melt parameters

Melt parameters (e.g. beam power, beam scan speed, beam pathway) are different from manufacturer to manufacturer and material to material. They change over time across multiple generations of machines from the same machine manufacturer. They also change over time for a given machine across multiple control software upgrades. Therefore, it is difficult to include specific information about melt parameter considerations from a design perspective, and so this section will include general information. When considering melt parameters are part of the design process, machine manufacturers and other literature should be consulted because intelligent use of melt parameters can enable gradient microstructures and microstructure control[6]. However, improper melt parameter usage can lead to unintended variation in microstructure and mechanical properties[5].

To successfully achieve thin-walled or small-featured parts (e.g. lattice structures) via PBF-EB/M, melt parameters, and specifically beam pathway, should be considered. Figure 7 a) schematically shows the beam pathway commonly used to melt parts, which consists of two steps: contour and fill (a.k.a. hatch). For successful printing of thin-walled or small-featured parts, when the feature size approaches the beam spot size (known from machine manufacturer), it is advisable to only perform contour and eliminate the fill step to avoid over-melting.

It is not feasible to discuss all melt parameter aspects of PBF-EB/M in this document, but one more aspect, Multispot melt, is shown schematically in Figure 7 b). The electron beam can be moved fast enough to keep many different melt pools advancing simultaneously, which reduces overall build time.



a) Standard melt steps comprised of contour and fill (a.k.a. hatch)

b) Multispot melt

Key

1 outer contour
2 inner contour(s)
3 fill/hatch
4 multispot melt

NOTE Source: GE Arcam

Figure 7 — Schematics showing melts

6.4 Anisotropy/heterogeneity of the material and part characteristics

6.4.1 General

The many influences between powder feedstock, processing – including complex thermal history –, and post-processing in PBF-EB/M can lead to anisotropic and heterogeneous microstructures and mechanical properties. Variation within a single part, between identical parts at different locations in the same build, and between identical parts in different builds have all been demonstrated[7][8]. Traditional verification and validation techniques are commonly used to qualify parts for a specific application. After validation/qualification, it is common to not change any aspect of processing (e.g. part orientation, exact build layout, melt parameters) to safeguard against unintentional changes in microstructure, mechanical properties, or part performance. Some specific types of microstructural anisotropy and heterogeneity will be discussed in the remainder of this clause.

6.4.2 Grain morphology

Grain morphology is commonly elongated in the build direction (Z-direction) due to epitaxial growth from the layer-wise PBF-EB/M process. In some cases (e.g. titanium), this anisotropy reduces mechanical characteristic values such as tensile strength and yield strength in the Z-axis. This should be taken into consideration when considering build orientation in regards to the principle loads.

Strong crystallographic texture in the build direction commonly accompanies the grain morphology anisotropy. However, small changes in various processing parameters (e.g. scan length) have been found to result in large variations in the character of the texture and resultant mechanical properties[5]. If these processing parameters are controlled properly, tuning the texture and mechanical properties can be possible[9].

6.4.3 Porosity

The formation of porosity is likely to occur in PBF-EB/M. Therefore, understanding the main types of porosity and their formation mechanisms is crucial to minimize the effect of porosity on mechanical properties and to optimize the PBF-EB/M process. There are three main types of porosity: gas porosity, lack of fusion (LOF) porosity, and keyhole porosity[9]. Gas porosity is thought to come from pores within the powder becoming entrained in the bulk material during PBF-EB/M processing[10]. Gas porosity is spherical, has a size range similar to the powder size range (usually less than approximately 100 µm), and usually only leads to a reduction in relative density on the order of tenths of a percent. Most PBF-EB/M powders are atomized, and some amount of powder particles with pores is common during atomization. Atomized powders are generally lower cost than other types of spherical powders, hence the motivation to use them in PBF-EB/M. Gas porosity has been shown to have only a small deleterious effect on quasi-static tensile elongation[11] and a negligible effect on high-cycle fatigue behaviour[12].

While gas porosity is inevitable for an atomized powder feedstock, LOF porosity and keyhole porosity are process-induced and therefore avoidable through process optimization. LOF porosity forms when there is insufficient energy to fully melt the powder layer. LOF pores tend to be relatively thin in the build direction (e.g. sometimes just a single layer) but can be quite large in the plane of the powder layer (e.g. possibly up to mm scale)[7]. Keyhole porosity forms when there is too much energy, which leads to a deep keyhole melt pool that can become unstable, collapse, and leave behind a pore. Keyhole pores tend to be spherical but with a size larger than gas porosity[13]. Keyhole and LOF pores have a significant negative effect on mechanical properties, especially fatigue[14], because they are much larger than gas porosity.

6.4.4 Intermetallic diffusion layer

As discussed in 6.3.5, PBF-EB/M commonly utilizes a build plate of different material than the AM build material. Because of this, an intermetallic diffusion layer commonly results and this should be taken into consideration when designing and orienting parts for PBF-EB/M. The intermetallic diffusion layer thickness needs to be determined for each combination of build plate and AM build material. This is normally in the order of hundreds of micrometers.

6.4.5 Chemistry heterogeneity

There is the potential for chemistry heterogeneity within a given part due to chemistry changes in powder over multiple reuse cycles coupled with suboptimal powder handling procedures. A good example to describe the potential for chemistry heterogeneity is titanium alloy Ti-6Al-4V. Due to the layer preheating commonly utilized in PBF-EB/M, unmelted Ti-6Al-4V powder in the build area experiences higher temperatures resulting in a small increase in oxygen content. This powder is recovered for reuse in subsequent builds, but if it is immediately recombined with powder that never left the reservoir and did not experience an oxygen increase, then improper mixing can lead to chemistry heterogeneities in the powder and parts in subsequent builds. It is therefore necessary to scrutinize the efficacy of powder mixing techniques to minimize chemistry heterogeneity. Further minimization of chemistry heterogeneity can be achieved by keeping powder recovered from the build area separate from powder that never left the reservoir and only recombining once all powder has been subjected to the build area. However, this powder handling technique requires purchasing larger batches of powder. It is also important to note that chemistry heterogeneities can also occur when mixing powder from different raw material lots with different chemistry.

6.4.6 Thermal history

The complex thermal history and rapid heating and cooling experienced in PBF-EB/M leads to formation of residual stress. However, the layer preheating and higher background temperature common for PBF-EB/M has been shown to sufficiently relieve residual stress for Ti-6Al-4V[14] and Inconel 718[9] yielding negligible residual stress in the as-built condition. Although these results are informative, they do not guarantee residual stress will be negligible for all as-built PBF-EB/M materials, part sizes, part geometries, scan strategies, and part packing density within a build.

As discussed in 6.3.7 (Figure 7 a)), normal scan strategy for PBF-EB/M includes two steps: contour and fill (a.k.a. hatch). It is important to note that these two steps commonly have different melt parameters and result in different microstructure and resultant properties. This should be taken into account when designing for PBF-EB/M.

The uniquely high background temperature arising from powder bed preheating in PBF-EB/M normally results in a slower cooling rate compared to PBF-LB/M. This should also be considered when designing for PBF-EB/M as cooling rate can have significant effect on resultant microstructure (i.e. grain size, phase content) and mechanical properties depending on the material system.

It has been shown that some material anisotropy/heterogeneities can be reduced by subsequent heat treatment[11]. The effect of heat treatments on anisotropy depends on the complete material cycle, including the build process, the heat treatment, and material composition.

Procedures, such as the manufacturing of test specimens, are often followed to ascertain microstructure and mechanical properties along various axes. Sample mechanical characteristic values for PBF-EB/M materials can be found from machine manufacturers, material specification standards (e.g. ASTM F2924[15]), and in the literature[16].

6.5 Surfaces

Melt pool solidification surfaces and particles of powder adhering to the surface of parts often lead to high surface roughness. Surface roughness depends largely on the upskin (υ) or downskin (δ) angle of the respective surface. Where angle $\delta = 0°$, downskin surfaces have significantly higher minimum roughness values than upskin surfaces. High surface roughness has been shown to have a large deleterious effect on mechanical properties, especially fatigue[17]. Typically, resulting surface roughness can be improved by adjusting process parameters locally. Post-production finishing can significantly reduce surface roughness.

6.6 Post-processing

6.6.1 General

As stated before, post-production finishing can often be necessary to reach final part characteristics needed. Typical post-processes comprise, but are not limited to, cleaning processes to remove loose powder material, heat treatments to reduce residual stresses and adjust material properties, sand blasting and other surface finishing to smooth surfaces, and mechanical post-processing (milling, grinding, etc.) to remove support structures or to generate functional surfaces.

6.6.2 Surface finishing

Resulting surface roughness might not meet requirements of parts exhibited to, for example, dynamic loads (fatigue strength) or fluid-dynamics. Hence, post processes such as sand blasting, machining or mechanical chemistry processes are applied.

6.6.3 Removal of powder residue

During production, the part is surrounded by sintered powder as it is built up layer-by-layer. Individual particles are left adhering to the part after it has been fabricated and removed from the powder cake. Removing these particles is generally the first step in the finishing process. Blasting with feedstock powder, carbon dioxide (i.e. dry ice) beads, or other abrasive media are common methods of removing powder residues post production. Ultrasonic agitation is also commonly used to assist in removal of powder. Powder removal from internal passages can be exceptionally challenging. When creating the build file for a part with internal passages, special consideration should be given to powder evacuation and access ports should be provided to allow for powder removal. In PBF-EB/M it is common to include layer preheating leading to sintering of powder not associated with the part being built. However, it is necessary to turn off layer preheating inside internal passages to prevent sintering and leave powder loose to facilitate post-build removal. Internal passage size should be larger than powder size distribution to allow for powder removal. Validation is necessary to show efficacy of powder removal process from a given geometry.

6.6.4 Removal of support structures

Parts produced by PBF-EB/M are generally fixed to support structures which have to be removed after production. Support structures can be removed mechanically, electromechanically or chemically. As noted earlier, this is often a required finishing procedure and the material to be removed should be taken into consideration during design.

6.6.5 Geometric tolerances

In general, the minimal feature value is dependent on material and processing condition, which include but are not limited to electron beam spot size, power density, powder particle size distribution, and layer thickness. Post-processing (e.g. machining processes) might be needed to meet tolerance specifications, especially for functional and mating surfaces.

The minimum surface roughness that can be achieved with parts produced in a powder bed by PBF-EB/M is limited due to particle adherence and stair casing. A better surface finish can be obtained with downstream treatments. Commonly used subtractive processes include abrasive blasting, vibratory finishing, flow grinding or electro-polishing. A gradual improvement in surface quality can be achieved by carrying out these processes in sequential order. An appropriate machining allowance is required for this purpose. When adapting design from another manufacturing method to AM, surfaces that do not require a specific finish should be identified. In fact, a design consideration can be the minimization of surfaces that do require post processing.

6.6.6 Heat treatment

6.6.6.1 Increasing the relative density of the material

Relative density (porosity) has a significant influence on the mechanical characteristics of the material, especially on fatigue and impact strength and less on tensile strength and hardness. Although PBF-EB/M typically achieves a relative density of at least 99 % of the reference value, density can nevertheless be further increased, by HIP, for example, if requirements are sufficiently high[18].

6.6.6.2 Influence on microstructure and mechanical properties

Post heat treatment processes are worth considering for some materials in order to attempt to arrive at more uniform and well-defined microstructure and mechanical characteristics[11].

6.6.6.3 Thermally induced residual stress

During PBF-EB/M the layer-wise build-up method combined with lateral shrinkage as each individual layer cools often generates some residual stresses in the finished part. However, it has been shown that higher temperatures from layer preheating common to PBF-EB/M successfully relieves residual stress during the process, resulting in as-built material with negligible residual[14] stress. Therefore, post-build residual stress relief heat treatments are often not necessary for PBF-EB/M before removing the part from the platform.

6.7 Design considerations

6.7.1 General

Consideration should be given specific to PBF-EB/M when designing typical geometric elements in order to achieve the desired results.

6.7.2 Cavities

In principle, it is possible to create cavities in parts during PBF-EB/M. The cavities will contain unmelted, and possibly loose (see 6.6.3), powder which can be removed post-production via dedicated openings, or left in place.

It can be useful to incorporate cavities into the design of large-volume parts in order to

— minimize warpage,

— improve process reliability,

— reduce build time,

— reduce mass, and

— eventually reduce material consumption.

Cavities should be designed with loading in mind. They can also be filled with mesh or bionic structures for reinforcement. These structures can also be used to optimize thermal or acoustic properties.

6.7.3 Gaps

Gaps that lie at least partially in the Z-axis should meet a minimum gap width to prevent the surfaces forming the gap from fusing. This minimum gap width depends largely on the material and process parameters used, but in the PBF-EB/M process should be larger than three times the layer thickness. Particle size distribution and the potential to remove powder should also be considered when determining minimum gap width. The minimum dimensions of gaps in a part which essentially lie parallel to the plane of the layer (i.e. normally parallel to the build platform) are typically hard to manufacture in PBF-EB/M. The statements are also true in terms of nesting parts (see 5.2 and 5.5) as long as post processes do not demand for wider gaps.

6.7.4 Wall thicknesses

In principle, minimal wall thicknesses in PBF-EB/M align with the range of the melt pool width. The ability of a wall to maintain its form will depend in particular on its support, the aspect ratio (height in relation to wall thickness) and the material used. Robust walls are typically several times thicker than the minimum width of the melt pool.

6.7.5 Holes and channels

Holes where the axes are produced in the Z-axis are typically limited by the aforementioned minimum gap width. In contrast, holes where the axes are produced counter to the Z-axis typically have a diameter several times greater than the layer thickness, as with gaps or channels that lie parallel to the plane of the layer. Thus, holes in the Z-axis can have smaller diameters and a better roundness than holes that run counter to the build direction.

Holes running counter to the Z-axis that exceed a certain diameter will require support in the overhanging areas, which can require post-processing. It is often the case that planning for a post process such as drilling will be the preferred method for creating a straight hole in an PBF-EB/M part.

Channels with a suitable cross-section can be constructed without support structures, if necessary, without a restriction on maximum size.

It is important to consider that holes below the critical diameter (although possible) will typically suffer a loss of circularity (i.e. become ovoid or “squashed”).

6.7.6 Integrated markings

Inscriptions and markings can be incorporated into the part during the build. In principle any type of inscription, be it etched or embossed, can be produced. Font style and size of lettering should be chosen with legibility in mind. Sans serif fonts with uniform wall thicknesses provide the best resolution. Font sizes of at least 24 are recommended for optimum legibility, although smaller fonts can be achieved on upward-facing surfaces. Recessed text offers better resolution than raised text[19]. If printed markings will remain on the final part, marking location should be considered to avoid negatively affecting part performance. Any part markings should be agreed upon between manufacturer and customer.

Inscriptions and markings can be used for

— signage in general and warning and safety instructions,

— symbols to facilitate assembly,

— nameplates with individual serial number,

— design elements,

— logos, and

— textures.

6.8 Example applications

6.8.1 Topology optimized bracket printed using stacking build layout (provided by GE Arcam)

6.8.1.1 General

Aim: Reduce mass and cost of a bracket design.

Result: Topology optimization lead to 55 % mass reduction, and stacked build layout lead to significant part cost savings.

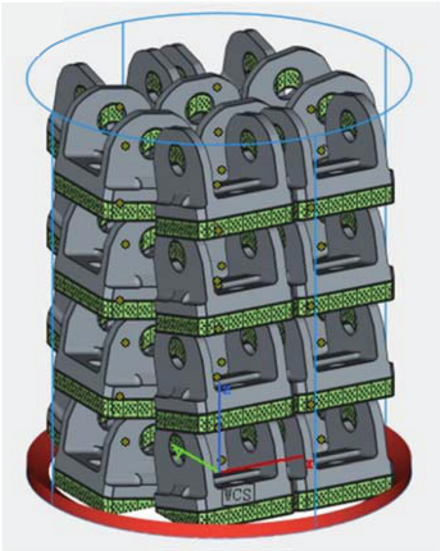
6.8.1.2 Boundary conditions and design considerations

— Machine: GE Arcam Q20+, Software Version: 5.2.52.7592, Material: Ti-6Al-4V

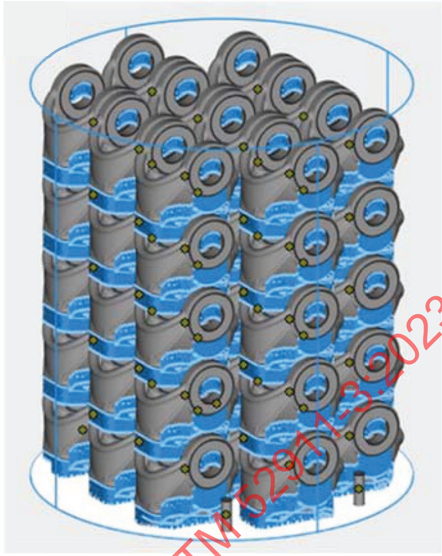
— This bracket application highlights the use of topology optimization and part stacking to reduce build time and part cost in PBF-EB/M. Topology optimization is often discussed from the perspective of final component performance, but the reduction in part volume can reduce build time and part cost. Renderings of the stacked build layouts are shown in Figure 8, and the job data (Table 5) shows a significant reduction in build time per part for the topology optimized design (3,7 h/part) compared to the original design (5,9 h/part). This reduction in build time per part correlates directly with part cost.

— The support design in this example application follows Figure 5 c), where supports are used but they do not connect to the build plate or parts beneath.

— Also seen in Table 5 are the advantages in per part cost when building in a stacked arrangement (3,7 h/part) compared to only a single layer of parts (5,2 h/part). This advantage is realized through a reduction in build time per part when considering the heat up and cool down time are shared by many more parts in the stacked configuration. If part geometry and build orientation are such that an overlap of parts in the Z-direction is possible, a further reduction in build time per part and per part costs may be realized (see 6.3.4).



a) Original bracket design



b) Topology optimized design

NOTE Source: GE Arcam

Figure 8 — Stacked build layouts

Table 5 — Job information for stacked and single layer build layouts of original and topology optimized bracket designs

	Parts per build parts	**Total build time** h	**Build time per part** h/part
Original bracket, Stacked build	28	164	5,9
Optimized bracket, Stacked build	50	186	3,7
Optimized bracket, Single layer build	10	52	5,2

NOTE Source: GE Arcam

6.8.2 Acetabular cup stacking design (provided by LimaCorporate Spa)

6.8.2.1 General

Aim: reduce part cost without compromising final part compliance through development of part stacking strategy.

Result: successful reduction of part cost while maintaining consistent part compliance.

6.8.2.2 Boundary conditions and design considerations

— **Machine: GE Arcam Q10 model, Software Version: 4.2.20, Material: Ti-6Al-4V**

— The given stacking example (Figure 9) follows the stacking strategy described in the present standard in Figure 5 a). The connected supports from higher-layer parts directly to the parts below

