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Additive manufacturing — Design —

Part 1: Laser-based powder bed fusion of metals

Fabrication additive — Conception —

Partie 1: Fusion laser sur lit de poudre métallique

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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 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.

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

Laser-based powder bed fusion of metals (PBF-LB/M) describes an additive manufacturing (AM) process and offers an additional manufacturing option alongside established processes. PBF-LB/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-LB/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-LB/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. It is intended that the series will include this document on PBF-LB/M, ISO 52911-2[1] on laser-based powder bed fusion of polymers (PBF-LB/P), and ISO 52911-3[2] on electron beam powder bed fusion of metals (PBF-EB/M). 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 is based on VDI 3405-3:2015. It provides support to technology users, such as design and production engineers, when designing parts that need to be manufactured by means of PBF-LB/M. It will help practitioners to explore the benefits of PBF-LB/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 process.

1) Under preparation.

2) Under preparation.

Additive manufacturing — Design —

Part 1:
Laser-based powder bed fusion of metals

1 Scope

This document specifies the features of laser-based powder bed fusion of metals (PBF-LB/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 http://www.iso.org/obp

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

3.1
curl effect
thermal and residual stress effect
<aspect of heat-induced warping> dimensional distortion as the printed part 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)

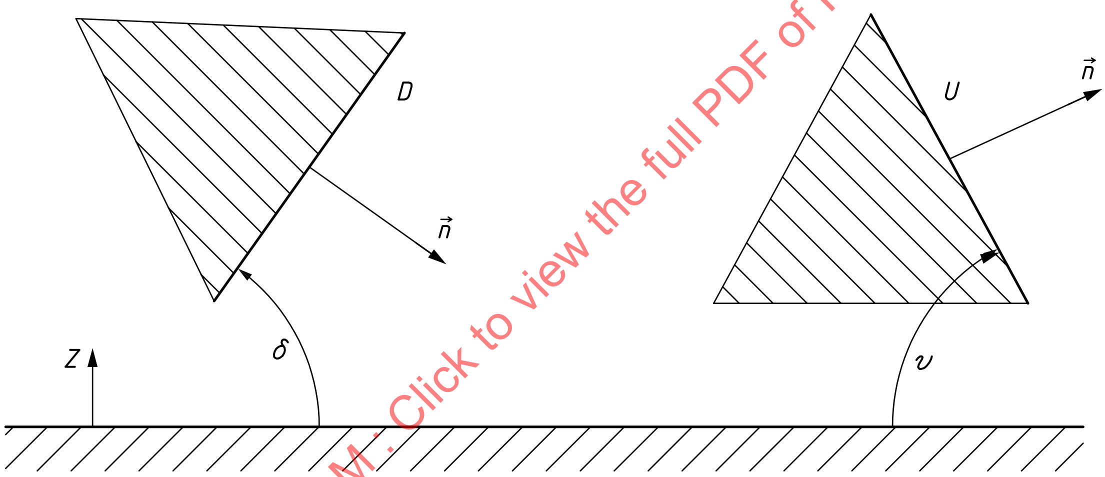
Note 1 to entry: See Figure 1.

3.4
upskin area
U
(sub-)area where the normal vector $\vec{n}$ projection on the *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 angle

$\vec{n}$ normal vector

D downskin (left) area

U upskin (right) area

υ upskin angle

SOURCE VDI 3405-3:2015.

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
D	downskin area	mm^2
I	island	mm^2
$\vec{n}$	normal vector	—
R_a	mean roughness	µm
R_z	average surface roughness	µm
U	upskin area	mm^2
δ	downskin angle	°
υ	upskin angle	°

4.2 Abbreviated terms

The following abbreviated terms are used in this document.

AM additive manufacturing

AMF additive manufacturing file format

CT computed tomography

DICOM digital imaging and communications in medicine

HIP hot isostatic pressing

MRI magnetic resonance imaging

PBF powder bed fusion

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

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)

STL stereolithography format or surface tessellation language

5 Characteristics of powder bed fusion (PBF) processes

5.1 General

Consideration shall 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. As with polymer powders PBF, metals PBF includes varying processing techniques. Unlike polymers, metals PBF often requires the addition of support structures (see 6.4.3). 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) beams to fully melt and fuse the powder particles together.

Electron beam-based melting and laser-based melting have similar capabilities, although the beam energy transferred from the electron beam to the metal is of a higher intensity and the process most commonly operates at higher temperatures than the laser counterpart, therefore typically also supporting faster build rates at lower resolutions. In general, since the powder bed is preheated and kept close to the melting temperature during the building operation, electron beam processes subject parts to less thermal induced stresses and have faster build rates, but the trade-off often comes with much longer times needed for the build chamber to cool down after the build cycle has been completed, and in general larger minimum feature sizes and greater surface roughness than laser melting.

5.2 Size of the parts

The size of the parts is not only limited by the working area/working volume of the PBF-machine. Also, the occurrence of cracks and deformation due to residual stresses can limit the maximum part size. Another important practical factor that can limit the maximum part size is the cost of production having a direct relation to the size and volume of the part. Cost of production can be minimized by choosing part location and build orientation in a way that allows nesting of as many parts as possible. The cost of the volume of powder required to fill the bed should be considered. Powder reuse rules impact this cost significantly. If no reuse is allowed then all 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 high. Limitations of conventional manufacturing processes do not usually exist, e.g. for:

  — tool accessibility, and

  — undercuts.

— A wide range of complex geometries can be produced, such as:

  — free-form geometries, e.g. organic structures,

  — topologically optimized structures, in order to reduce mass and optimize mechanical properties, and

  — infill structures, e.g. honeycomb.

— 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 en 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 shall be taken into consideration during product design.

— Shrinkage, residual stress and deformation can occur due to local temperature differences.

— The surface quality of AM parts is typically influenced by the layer-wise build-up technique (stair-step effect). Post-processing can be required, depending on the application.

— Consideration shall be given to deviations from form, dimensional and positional tolerances of parts. A machining allowance shall therefore be provided for post-production finishing. Specified geometric tolerances can be achieved by precision post-processing.

— Anisotropic characteristics typically arise due to the layer-wise build-up and shall 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.

— Powder removal post processing is necessary.

5.5 Economic and time efficiency

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 different criteria for optimization are available depending on the number of units planned.

In the case of a one-off production, height is the factor that has the greatest impact on building time and build costs. Parts should be orientated in such a way that the build height is kept to a minimum.

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 orientated so as to minimize the number of build runs required. Strategies for nesting can also be included to maximize the available build space. 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 recycling of powder can affect the powder size distribution, surface characteristics and alloy composition, and this in turn affects final part characteristics. In addition, the reusable powder characteristics and therefore recyclability can be different for electron beam-based and laser beam-based powder bed fusion. The number of times a powder can be recycled is dependent on the machine manufacturer and the part specification.

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)

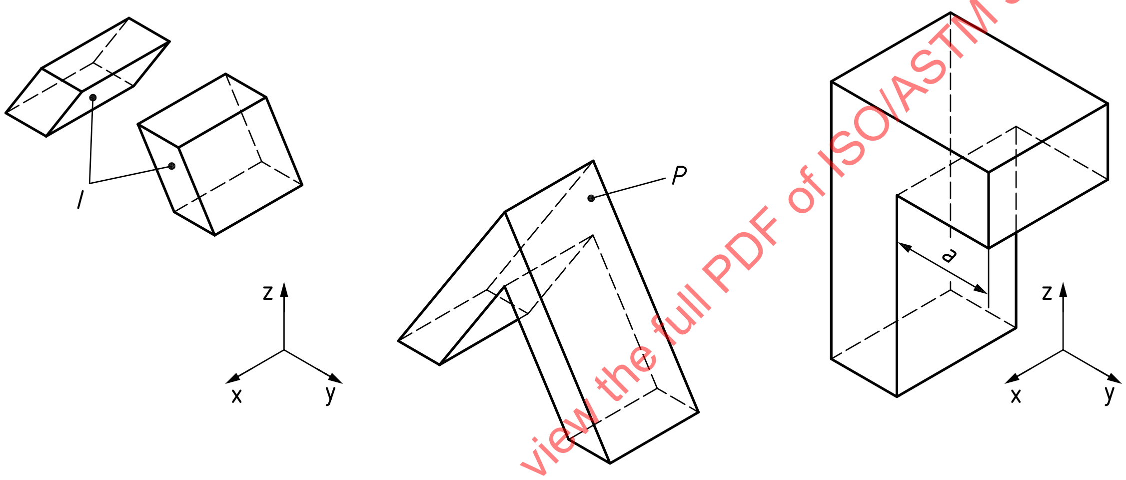
5.6.1 General

Since AM parts are built up in successive layers, separation of features can 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 this connection will occur shall 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

SOURCE VDI 3405-3:2015.

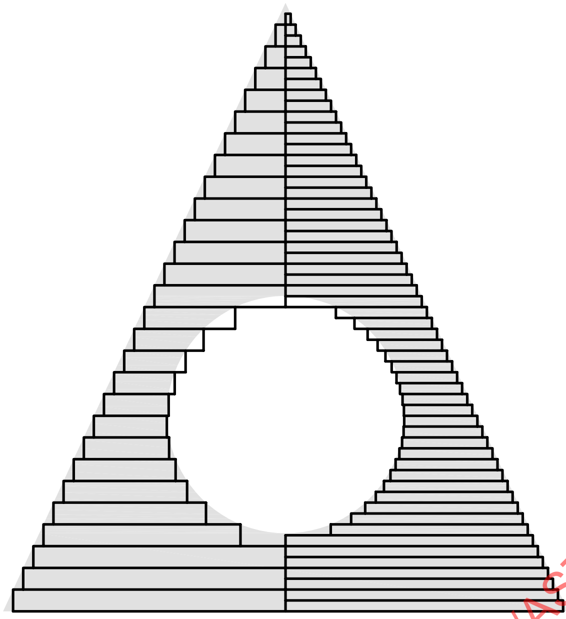
Figure 2 — Islands *I* (left) and overhang *a* (right) during the construction of part *P* in *z*-axis

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* 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* of Figure 2, which can lead to the machine standstill.

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).



SOURCE VDI 3405-3:2015.

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 tool-based manufacturing processes. For this reason, post-processing can be necessary to meet (customer) requirements. Post-processing may include subtractive manufacturing, surface finishing, thermal processing, or other operations according to ISO/ASTM 52910.

In this respect, it is particularly important to be aware of and consider process parameters that 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 defined using the right-hand rule and the normal vector. The STL file format is recognized as the quasi-industry data exchange format. Additional formats include AMF, which is described in ISO/ASTM 52915, and 3MF, which is being promoted by an industry consortium led by Microsoft[3].

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 defined 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 at least 5 times smaller than the resolution of the AM process. As a result, a chord height setting of

3) This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of the product named.

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, metres, 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.

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 laser-based powder bed fusion of metals (PBF-LB/M)

6.1 General

6.1.1 Selecting PBF-LB/M

PBF-LB/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 or channels, and/or features with undercuts or structures that cannot be realized by casting, forging or metal cutting processes. The flexibility of PBF-LB/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 can be an important consideration when choosing PBF-LB/M, even when PBF-LB/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 can be applied in a similar field of application as PBF-LB/M are: PBF-EB/M, directed energy deposition of metals, or lost model 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-LB/M process. This can 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 can be a part of the design cycle.

6.2 Material and structural characteristics

Metals and metal alloys are the materials most commonly used for PBF-LB/M (see Annex A). Preferred methods of production for metal powders typically include plasma or gas atomization in an argon or nitrogen 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 should 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)[5]. These factors all affect the characteristics of the part being manufactured. For this reason, design for PBF-LB requires taking processing environments into consideration as well.

Table A.1 shows a selection of the material classes that are available to PBF-LB/M processes. In addition to this overview, there are some other materials that can be used such as copper alloys, gold and silver, tungsten and tantalum. As AM technology advances, it is expected that other materials will become available in the near future. 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-LB/M as well.

It is possible to achieve a relative part density close to 100 %[6]. Figure 4 depicts a microstructure after PBF-LB/M:

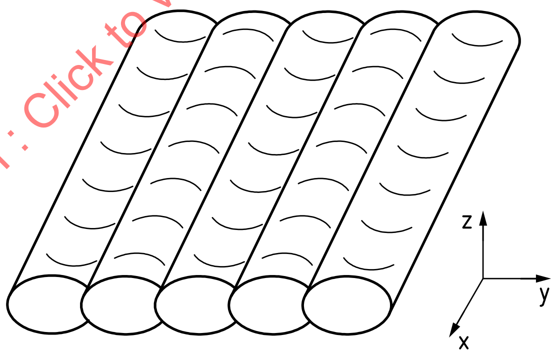
a) shows a longitudinal section (in the *z*–*y* plane) of a part made from material 1.2709 with the overlapping tracks clearly visible;

b) shows the overlapping tracks of a single layer (*x*–*y* plane).

The microstructure created by the PBF-LB/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 correlates directly with the macro- and microstructure formed.

Post heat treatments of parts produced by metal AM are applied commonly for release of residual stresses and tuning material properties.

a) Longitudinal section of a part made from material 1.2709



b) Overlapping tracks in a single layer

SOURCE VDI 3405-3:2015.

Figure 4 — Microstructure after PBF-LB/M

6.3 Support structures

The PBF-LB/M process 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-LB/M processes serve multiple functions, including

— dissipation of heat,

— securing the part to the build platform,

— 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 2 provides guidance on the use of support structures in PBF-LB/M processes. The values used in Table 2 are general guidelines, and both process parameters and material specifics 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-LB/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 can lead to an increase in build time but can also significantly reduce effort in post-processing to remove the support structures.

Table 2 — Guidance on the use of support structures

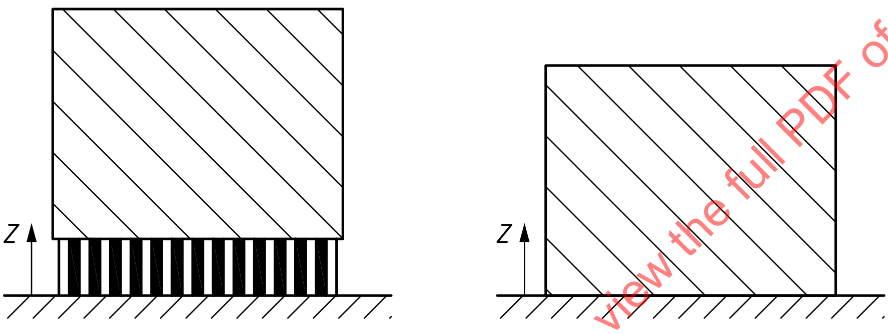
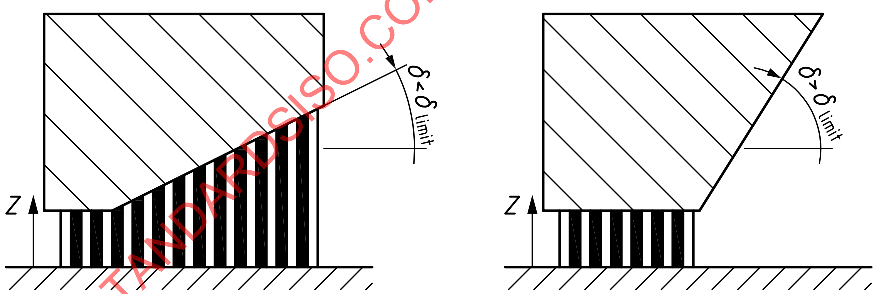
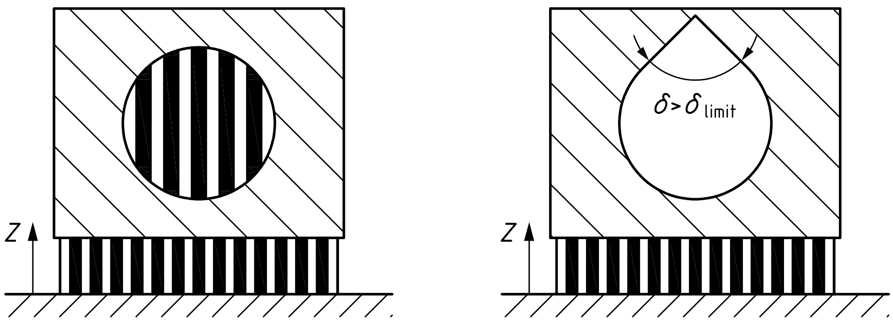
	Left: Support structures connecting the part to the build platform Right: Part connected directly to the build platform without support structures *Comment 1: In order to avoid the risk of cracks, a fillet can be foreseen between the part and the plate (not included in sketch).* *Comment 2: When supporting a part directly to the build substrate, removal through wire electrical discharge machining can be complicated due to trapped powder and uneven cutting action.*
	Left: Faces with downskin angle $\delta < \delta_{limit}$ 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.) above the regarded face. Right: Faces with downskin angle $\delta > \delta_{limit}$ do not require support structures. The surface quality may be adversely affected, depending on the angle.
SOURCE: VDI 3405-3:2015 (except for right figure in middle row).	

Table 2 *(continued)*

	Left: Hole with internal support structure Right: Shape of hole modified to avoid use of support structures as per Reference [7]. *Comment: If drilling operation is needed after PBF-LB/M, this shape is difficult to machine. Hence, in some cases, it can 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 to not foresee a hole and fully drill instead (e.g. titanium).*
SOURCE: VDI 3405-3:2015 (except for right figure in middle row).	

6.4 Build orientation, positioning and arrangement

6.4.1 General

The orientation, positioning and arrangement of parts during PBF-LB/M have an impact on process costs, process stability and various component characteristics. Factors that help to determine proper orientation, positioning and arrangement are discussed in 6.4.2 to 6.4.4.

6.4.2 Powder spreading

Most PBF-LB 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 can often scrape or interfere with the part as each successive layer is applied. Parts shall therefore be orientated, positioned and arranged so as to minimize the frictional forces generated during scraping. The following points should be considered (see Table 3):

— 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 3).

Table 3 — Arrangement of critical elements in the build space of the machine

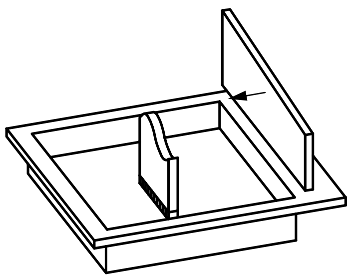
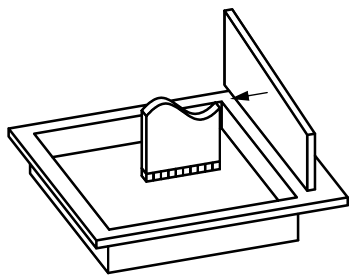
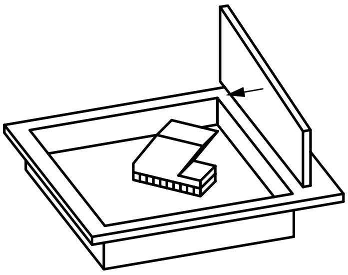
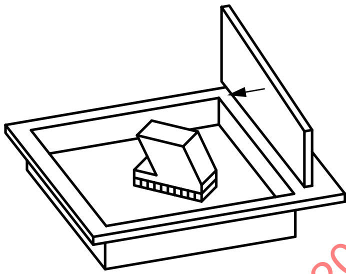
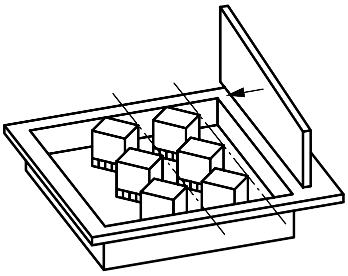
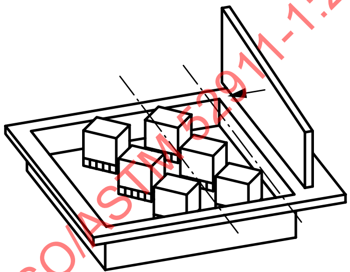
Description	Poor	Good
Longitudinal geometries should be oriented in a way that the contact length with the spreading system is minimized.		
SOURCE: VDI 3405-3:2015.		

Table 3 *(continued)*

Description	Poor	Good
Critical geometries 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°.		
Multiple parts should be positioned in a way that the contact length with the spreading system is minimized (arranged with an offset).		
SOURCE: VDI 3405-3:2015.		

6.4.3 Support structures design

Build orientation and 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.).

Support structure design can be realized in various shapes (e.g. block shape, web shape) and densities (e.g. gap width, web diameter). 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

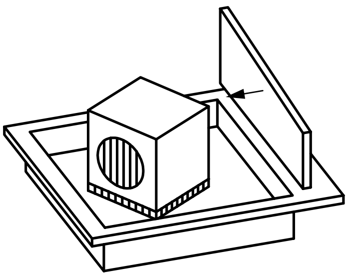
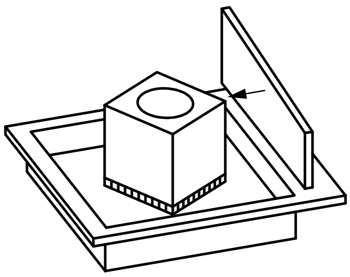
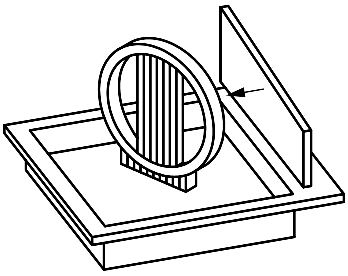
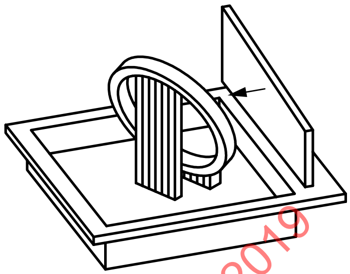
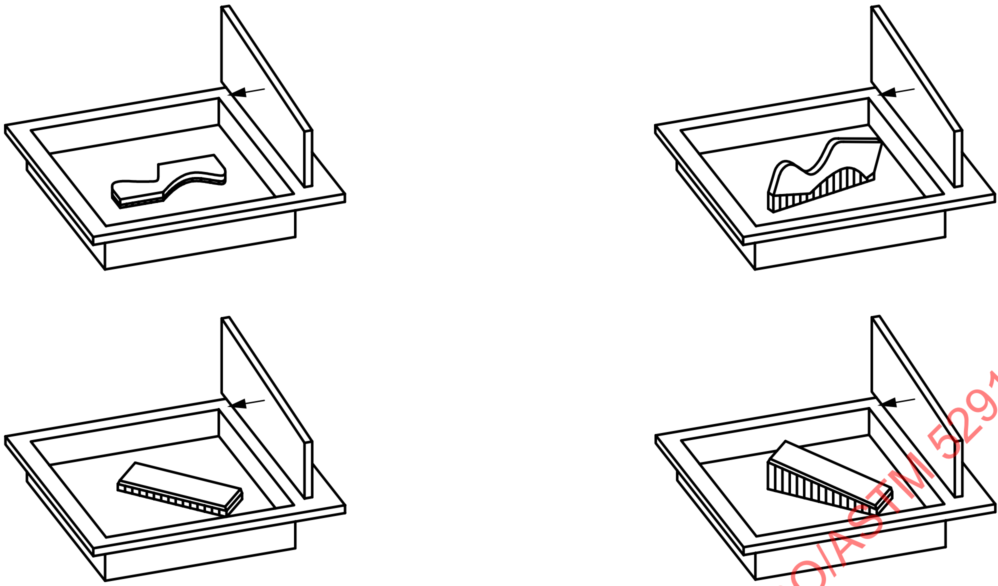
Description	Poor	Good
Avoiding support structures through part orientation that leads to least need for support structures.		
SOURCE: VDI 3405-3:2015.		

Table 4 *(continued)*

Description	Poor	Good
Avoiding post-processing effort through support structure design that considers the desired post process for its removal.		
SOURCE: VDI 3405-3:2015.		

6.4.4 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. Warping of large part surfaces can be prevented through the use of suitably designed support structures (see Figure 5) and the application of heat. In this manner, exposure of the large surface can be divided between different layers throughout a build.



a) Poor

b) Good

SOURCE VDI 3405-3:2015.

Figure 5 — Examples showing how to avoid the curl effect when irradiating large surfaces

6.5 Anisotropy of the material characteristics

Anisotropic mechanical characteristics result from the layer-on-layer construction process. In many cases, this reduces mechanical characteristic values such as tensile strength and yield strength in the *z*-axis[8][9]. This shall be taken into consideration when considering build orientation in regard to the principle loads. It has been shown that material anisotropy can be reduced by subsequent heat treatment. 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 mechanical properties along various axes. Sample mechanical characteristic values for tool steel 1.2709 can be found in VDI 3405-2 and for aluminium alloy in VDI 3405-2.1.

6.6 Surface roughness

Particles of powder adhering to the surface of parts can cause 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. Average roughness values below 140 µm are typically achievable in untreated surfaces (see VDI 3405-2). Typically, resulting surface roughness can be improved by adjusting process parameters locally. Post-production finishing can significantly reduce surface roughness.

6.7 Post-production finishing

6.7.1 General

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.

6.7.2 Surface finishing

Resulting surface roughness (see 6.6) sometimes does 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.

6.7.3 Removal of powder residue

During production, the part is surrounded by unmelted 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. Cleaning with compressed air and abrasive blasting are common methods of removing powder residues post production. Powder removal from internal passages can be exceptionally challenging. When creating the build file for a part with internal passages, special consideration shall be given to powder evacuation and access ports shall be provided to allow for powder removal.

6.7.4 Removal of support structures

Parts produced by PBF-LB/M are generally fixed to support structures which are required to be removed after production. Support structures can be removed mechanically, electromechanically or chemically. This is often a required finishing procedure and the material to be removed should be taken into consideration during the design phase. Due to residual stress, before removing parts from the build platform a stress relieving heat treatment is often necessary.

6.7.5 Adjusting geometric tolerances

Like most AM processes, PBF-LB/M can be used to produce very complex geometries; however, in most cases, the resulting deviations from form, dimensional and positional tolerances do not meet specifications. Tolerances in the order of magnitude of around ±0,2 % with minimal value 0,2 mm are achievable with PBF-LB/M using current state-of-the-art technology. In general, the minimal feature value is dependent on material and processing condition, e.g. the laser spot size and power density. Tolerance specifications are often not achieved without post-processing, and functional surfaces and fits should therefore be finished to enable them to fulfil their function. Manufacturing processes (e.g. machining processes) capable of producing sufficient accuracy are suitable for this purpose.

The minimum surface roughness that can be achieved with parts produced in a powder bed by PBF-LB/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[1]. An appropriate machining allowance should be provided 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 should be the minimization of surfaces that do require post processing.

6.7.6 Heat treatment

6.7.6.1 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. This depends on the actual manufacturing process. Although PBF-LB/M as per VDI 3405-2 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[10].

6.7.6.2 Influence on microstructure and ductility

Post heat treatment processes are worth considering for some materials in order to attempt to arrive at more uniform and well-defined mechanical characteristics. Geometric deformations and mechanical characteristics can be modulated by carefully adjusting the temperature over time[11].

6.7.6.3 Reducing thermally induced residual stress

During PBF-LB/M, the layer-wise build-up method combined with lateral shrinkage as each individual layer cools often generates significant residual stresses in the finished part. Heat treatment shall be used for stress relief before removing the part from the platform.

6.8 Design considerations

6.8.1 General

Consideration shall be given specific to PBF-LB/M when designing typical geometric elements in order to achieve the desired results (see for example Reference [7]).

6.8.2 Cavities

In principle, it is possible to create cavities in parts during PBF-LB/M. The cavities contain loose, unmelted 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.

6.8.3 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[12]. This minimum gap width depends largely on the material and process parameters used, but in the PBF-LB/M process should typically be larger than the width of the melt pool. 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 difficult to manufacture in PBF-LB/M. The requirements are similar for nesting parts (see 5.2 and 5.5) as long as post processes do not have a requirement for wider gaps.

6.8.4 Wall thicknesses

In principle, minimal wall thicknesses in PBF-LB/M align with the range of the melt pool width. The ability of a wall to maintain its form depends in particular on its orientation in relation to the coating direction, 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.

6.8.5 Holes and channels

Holes where the axes are produced in the *z*-axis are typically limited by the minimum gap width; see 6.8.3. 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 can 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 is the preferred method for creating a straight hole in an PBF-LB/M part. Channels with a suitable cross-section can be constructed without support structures if necessary without a restriction on maximum size.

NOTE Holes below the critical diameter (although possible) typically suffer a loss of circularity (i. e. become ovoid or "squashed").

6.8.6 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. Typically, recessed text offers better resolution than raised text.

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.

6.9 Example applications

6.9.1 General

The applications described in this subclause illustrate the opportunities afforded by PBF-LB/M for addressing two different problems. The first example (6.9.2) explains how this technology can be exploited to produce complex free-form parts. The second example (6.9.3) shows how design flexibility facilitates the production of a hydraulic block which uses less material than conventionally produced parts while performing the same function. Both parts are shown in their raw post-production state with support structures removed.

6.9.2 Integral design (provided by CETIM — Technical Centre for Mechanical Industry)

6.9.2.1 General

Aim: To reduce the number of components in a welded assembly comprising six individual machined parts.

Result: Reduced to a single part, 40 % mass lower.

Figure 6 a) shows the original welded assembly and Figure 6 b) shows the modified result from topology optimization in order to reduce the mass of the part by PBF-LB/M.

a) **Original welded assembly**

b) **Modified result design by topological optimization and produced by PBF-LB/M**

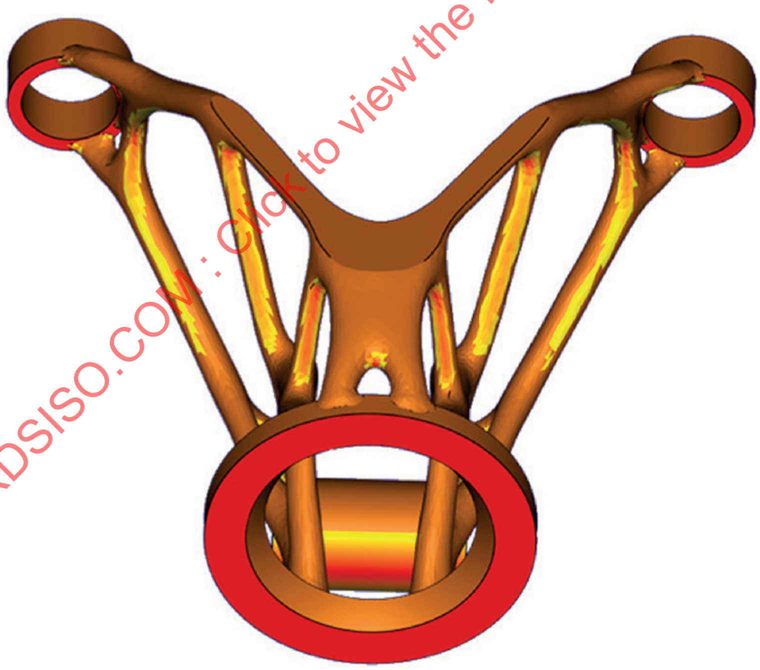
Figure 6 — Component of rotating machine to produce cables

6.9.2.2 Case study design guidelines

In this case, topological optimization software was used which does not consider AM rules.

The part is fabricated by PBF-LB/TiAl6V4 and after topological optimization the following design rules to optimize the shape of the part were applied.

— Checking angle surfaces $\delta > \delta_{\text{limit}}$ with $\delta_{\text{limit}} = 45°$ (see Figure 7).



The shape of the part should be modified to avoid manufacturing supports in the yellow-orange area (see Figure 8). In the red area, the surfaces are functional. They are supported.

Figure 7 — Initial shape: result from topological optimization

— Checking maximum cantilevered to avoid powder coating problems due to friction between the part and the recoating system $\frac{t}{l} > \frac{1}{8}$ where t is the thickness and l is the length (see Figure 8).