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Additive manufacturing — Design —

Part 2: Laser-based powder bed fusion of polymers

Fabrication additive — Conception —

Partie 2: Fusion laser sur lit de poudre polymère

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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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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

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 polymers (LB-PBF/P) describes an additive manufacturing (AM) process and offers an additional manufacturing option alongside established processes. LB-PBF/P 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 LB-PBF/P 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 LB-PBF/P 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 ISO 52911-1 on laser-based powder bed fusion of metals (LB-PBF/M), this document on LB-PBF/P, and ISO 52911-3[1)] on electron beam powder bed fusion of metals (EB-PBF/M). Clauses 1 to 5, where general information including terminology and the PBF process is provided, are similar throughout the series. The subsequent clauses focus on the specific technology.

This document is based on VDI 3405-3:2015[8]. It provides support to technology users, such as design and production engineers, when designing parts that need to be manufactured by means of LB-PBF/P. It will help practitioners to explore the benefits of LB-PBF/P and to recognize the process-related limitations when designing parts. It also builds on ISO/ASTM 52910[4] to extend the requirements, guidelines and recommendations for AM design to include the PBF process.

1) Under preparation.

Additive manufacturing — Design —

Part 2:
Laser-based powder bed fusion of polymers

1 Scope

This document specifies the features of laser-based powder bed fusion of polymers (LB-PBF/P) 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 http://www.electropedia.org/

3.1
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.

3.2
downskin angle
δ
angle between the plane of the build platform and the *downskin area* (3.1)

Note 1 to entry: The angle lies between 0° (parallel to the build platform) and 90° (perpendicular to the build platform).

Note 2 to entry: See Figure 1.

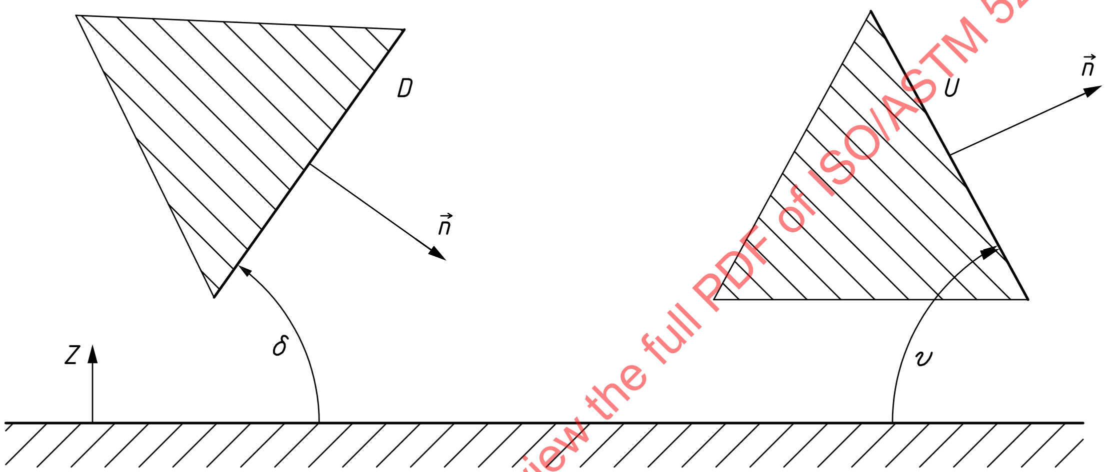
3.3
upskin area
U
(sub-)area where the normal vector $\vec{n}$ projection on the z-axis is positive

Note 1 to entry: See Figure 1.

3.4
upskin angle
υ
angle between the build platform plane and the *upskin area* (3.3)

Note 1 to entry: The angle lies between 0° (parallel to the build platform) and 90° (perpendicular to the build platform).

Note 2 to entry: See Figure 1.



Key
z build direction

SOURCE VDI 3405-3:2015.

Figure 1 — Upskin and downskin areas *U* and *D*, upskin and downskin angles *υ* and *δ*, normal vector $\vec{n}$

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	—
P	part	mm^3

Table 1 *(continued)*

Symbol	Designation	Unit
Ra	mean roughness	µm
Rz	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

CAD computer aided design

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

LB-PBF laser-based powder bed fusion

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

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

MRI magnetic resonance imaging

PBF powder bed fusion

STL stereolithography format or surface tessellation language

3MF 3D manufacturing format

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.

5.2 Size of the parts

The size of the parts is limited by the working area/working volume of the PBF-machine. Also, the occurrence of cracks and deformation due to residual stresses limits the maximum part size. Another important practical factor that limits 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. Also, the cost of powder needed to fill the bed to the required volume (part depth × bed area) may be a consideration.

Powder reuse rules impact this cost significantly. If no reuse is allowed, then all powder is scrapped regardless of solidified volume.

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:

— Parts can be manufactured to near-net shape (i.e. close to the finished shape and size), without further post processing tools, in a single process step.

— 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[17],

  — topologically optimized structures,

  — infill structures, e.g. honeycomb, sandwich and mesh structures.

— The degree of part complexity is largely unrelated to production costs.

— Assembly and joining processes can be reduced through single-body construction.

— Overall part characteristics can be selectively configured by adjusting process parameters locally.

— Reduction in lead times until 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 injection moulding and casting. Material properties can be influenced significantly by process settings and control.

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 build costs. Parts shall be oriented in such a way that the build height is kept to a minimum, provided that the geometry permits such an orientation.

— If the intention is to manufacture a larger number of units, then the build space shall be used as efficiently as possible. Provided that the part geometry permits such orientation, strategies for reorientation and nesting shall be utilized to maximize the available build space.

— The powder that remains in the system after a build can be reused in some cases. Reuse depends on the application, material, and specific requirements. Powder changes can be inefficient and time consuming. Although they are necessary when changing material type, powders from same-material builds can be reused. It is important to note, however, that recycling of powder can affect the powder size distribution, which in turn affects final part characteristics. The number of times a powder can be recycled is dependent on the machine manufacturer and the material.

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

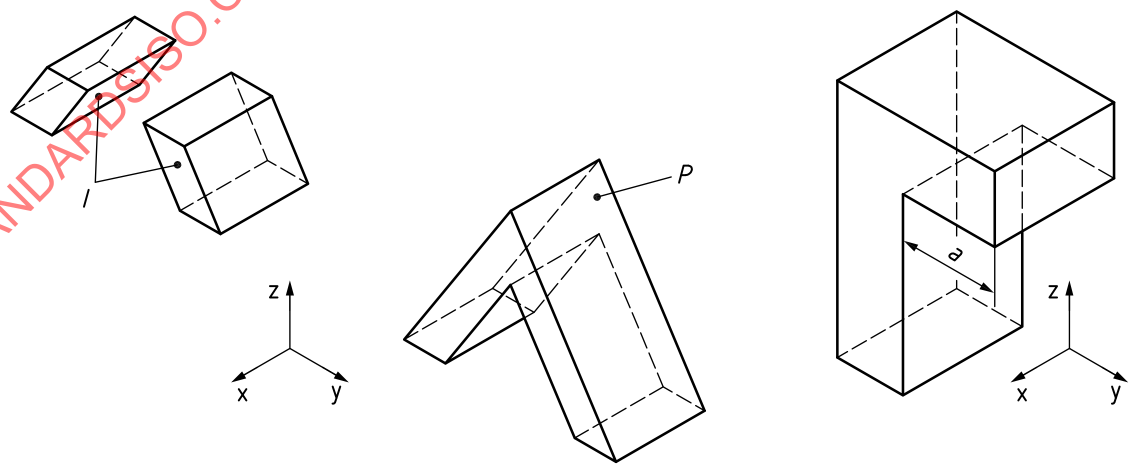
5.6.1 General

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 in 5.6.2 to 5.6.4 shall 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 at some stage of 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.



SOURCE VDI 3405-3:2015.

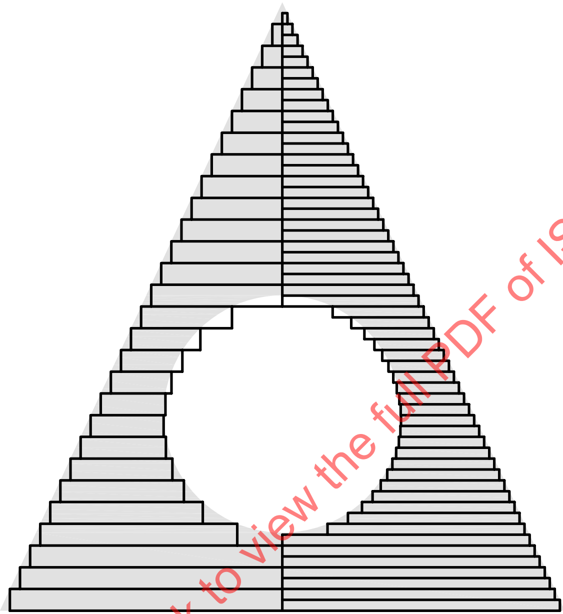
Figure 2 — Islands *I* (left) and overhang *a* (right) during the construction of part *P* in *z*-axis

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.

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 that 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[5].

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 significant 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 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 is 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. Geometric resolution is controlled by the imager resolution.

6 Design guidelines for laser-based powder bed fusion of polymers (LB-PBF/P)

6.1 General

The design guidelines in this clause take into account the specific characteristics of LB-PBF/P. In general, the PBF process for polymers is similar to that for metals as it includes a thermal source for inducing fusion between the powder particles, a method for limiting powder fusion to a zonal region per layer, as well as mechanisms to add the powder layers. Materials typically used are polyamides (PA 11, PA 12 and their derivatives), although other materials can be processed as well. Some unfused powders can be recycled in subsequent builds, usually by mixing the recycled powder with virgin powder. In addition, materials can be filled or mixed with other materials, such as glass and carbon fibres, to improve strength and thermal, electrical and fire-retardant properties. This clause describes the implications of

— build orientation, positioning and arrangement,

— material properties of fused polymers,

— surface characteristics of fused polymers,

— aspects of post-production finishing and

— other design considerations[8].

6.2 Material and structural characteristics

Different powdered thermoplastics are available for LB-PBF/P, of which semi-crystalline materials are the most widely used. In polymer PBF, the powder bed is pre-heated and the temperature is maintained a few degrees below the melting temperature of the polymer. The elevated powder bed temperature not only reduces the required energy input from the laser for melting but also prevents the molten polymer from recrystallizing during the build process. Recrystallization during the build process contributes to part shrinkage and warpage, which can lead to a failed build. PBF polymers typically exhibit a melt temperature that is higher than the recrystallization temperature, and the difference defines a processing window that can be exploited by the PBF process[8]. The typically broad softening range of amorphous thermoplastics, on the other hand, impedes this type of process control. Areas exposed to the laser beam solidify rapidly. As a result, the viscous flow associated with fusion and stress relaxation are impeded, and the parts are characterized by high porosity and low mechanical strength[9][10][11].

Due to their desirable characteristics for polymer PBF, the most common polymers are semi-crystalline polyamides, including PA 12, PA 11 and their derivatives, such as glass-filled PA 12 and flame-retardant PA 11. In special cases, amorphous, debindable, elastomeric, polymer-polymer blends and thermoset materials can also be processed with PBF. A selection of available materials is shown in Table 2.

NOTE Material data sheets are available from material suppliers and service bureaux.

Table 2 — Overview on available materials for LB-PBF/P[12]

Polymer powder material	Application field	Main properties
Semi-crystalline polymers e.g. PA 12	(Semi-)rigid polymer parts	Long-term usability
High-temperature semi-crystalline polymers e.g. PEEK	High temperature polymer parts	Long-term usability
Amorphous polymer e.g. PS	Investment casting and lost patterns	Accurate and partially porous
Sacrificial polymers used as binder e.g. PMMA	Metal or ceramic parts	Thermally degradable and amorphous polymers
Filled semi-crystalline polymers e.g. PA-GF, PA-Al, PA-Cu	Parts with special properties	Long-term usability and can withstand high loading
Elastomeric polymers e.g. TPU	Elastic parts	Long term usability
Polymer-polymer blends	Emerging applications	Specialized applications
Thermo-setting polymers e.g. epoxy resin	Emerging applications	Uses chemical binding

Material properties depend on a variety of factors, including the type of polymer, particle size, degree of powder recycling and processing conditions. In particular, the temperature distribution during the build process has a significant effect on material properties. Temperature distribution in the build platform is affected by the extent and uniformity of preheating, part density in the build platform, laser energy density, and the rate of post-build cool down. For these reasons, it is difficult to make blanket statements about the achievable material structure and properties[10]. However, large scale studies of polyamides have indicated that strengths comparable to injection moulded parts can be achieved with minor variability (approximately 10 %), even for parts oriented orthogonal to the build plane, whereas elongation at break is typically much lower than that for injection moulded parts[8].

6.3 Anisotropy of the material characteristics

LB-PBF/P parts generally have considerable anisotropy between orientations. Typical ranges for the mechanical characteristic values of PA 12 derived from an interlaboratory test are indicated in VDI 3405-1[7]. Anisotropy within the build plane, i.e. between x- and y- directions, is very low when alternatingly intersecting scan directions are used[13]. In contrast, a particularly high anisotropy occurs between the build plane and the *z*-axis (*z*-direction). Strength and elongation at break in particular show greater differences between orientations, while the modulus of elasticity differs by no more than 6 %. Tensile strength between orientations can vary by up to 25 %, whereas ideally the deviation should be significantly below 25 %[11]. In the case of elongation at break, the difference can range from 20 % to 70 % depending on the machine and the parameters. Elongation at break therefore exhibits the strongest anisotropic behaviour, whereby a transition can occur in some cases from a ductile fracture behaviour with yield strength within the build plane to a brittle fracture in the build direction. The highest strength and elongation at break are achieved within the build plane, whereas the modulus of elasticity is often higher in the build direction. The characteristic values for the remaining build orientations lie between these extremes, whereby elongation at break and strength in particular decrease as the angle to the horizontal increases. Furthermore, anisotropy of the part's mechanical properties in the margins and corners of the build space is generally more pronounced than in the centre due to lower preheating temperatures caused by variations in the powder bed temperature. This effect occurs in particular when alternative materials to PA 12 are used.

6.4 Build orientation, positioning and arrangement

6.4.1 General

The orientation, positioning and arrangement of parts have a significant effect on part characteristics in LB-PBF/P. The build orientation of the part shall be agreed upon between the customer and the part provider and shall be documented so it can be used for inspection, finishing, or rework. The build orientation should follow the rules given in ISO/ASTM 52921[6]. Therefore, it shall be taken into account that considerations from the point of view of manufacturing can differ from considerations to achieve optimal performance of the part. The effects of build orientation on mechanical characteristics and surface reproduction accuracy are described in later clauses. Other aspects are briefly discussed in 6.4.2 to 6.4.5.

6.4.2 Powder coating

During LB-PBF/P, contact forces can be transferred from the recoater to the parts as the layers are deposited. In a well set-up machine, these forces can be very low, but shall nevertheless be taken into account when orientating filigree structures.

Whenever possible, very thin vertical walls shall not be aligned parallel to the coater.

6.4.3 Part location in the build chamber

LB-PBF/P is a thermal process. The build chamber is preheated to only a few degrees Kelvin below the melting temperature of the material. Support structures are not normally needed during LB-PBF/P on account of this preheating. However, temperature distribution is often inhomogeneous. It is generally colder in the corners and around the edges. Furthermore, the surrounding volume has an impact on heat distribution. Cooler temperatures at the edges of the build chamber can lead to diminished part accuracy and material properties. If a particularly high level of accuracy or material properties is required for a part, it is best to position it near the centre of the build chamber. Zonal heaters and other technologies can help compensate for temperature differences between the inside and outside regions of the build chamber, but obviously the most external regions of the build chamber are at greater risk of uncontrolled temperature deviations.

6.4.4 Oversintering

As the laser scans the powder bed to fuse powders into a fabricated part, it creates heat affected zones within and around the intended part. At the edges of the scanned regions, some of the surrounding powder can be heated sufficiently to cause it to fuse to the edges of the part. Called oversintering, this phenomenon can result in growth in part dimensions, especially on downward facing surfaces. Typically, upward facing surfaces have sharper details than downward facing surfaces. For example, small letters on top surfaces resolve with more precision than those on bottom or side surfaces.

6.4.5 Packing parts efficiently in the build chamber

Since LB-PBF/P does not require support structures (overhangs and undercuts are supported by surrounding unsintered powder), it allows far more freedom to nest parts than other additives techniques. Therefore, cost-effective production depends on making efficient use of the available build space by designing parts that can be packed compactly or nested during fabrication.

6.5 Surface roughness

As with mechanical characteristics, surface characteristics are strongly dependent on surface orientation. The usual average surface roughness *Ra* lies between 10 µm and 20 µm for PA 12. A higher or lower surface roughness can be obtained using alternative materials or by varying the particle size. Vertical surfaces have surface roughnesses in the middle of the indicated interval. Surfaces parallel to the build plane have the lowest surface roughness, while upskin surfaces with an upskin angle between 10° and 25° have the highest surface roughness values. This is due to the particularly pronounced stair-step effect produced by the layer-wise build-up. This effect is less pronounced on downskin surfaces with equivalent angles, since the steps are partially evened out by oversintered powder[14]. Layer thickness is the main factor influencing roughness in LB-PBF/P[12]. An increase in layer thickness leads to a simultaneous increase in stair-stepping effects, producing greater roughness even on vertical surfaces.

6.6 Post-production finishing

Laser-sintered parts have high surface roughness compared with machined or injection-moulded parts. However, suitable finishing processes can increase the applications for laser-sintered parts. Furthermore, carefully selected finishing methods can influence the appearance, strength and porosity and thus the density of a laser-sintered part. Finishing can improve the surface quality to meet the following requirements[15][16]:

— functional requirements:

  — corrosion resistance;

  — wear resistance;

  — sliding properties;

  — roughness;

  — hardness;

  — strength;

  — density;

— decorative requirements:

  — colour;

  — sheen;

  — roughness;

  — smoothness.

Finishing processes of polymers generally involve a combination of surface treatments and surface coatings to meet diverse surface quality requirements. Abrasive blasting is a standard finishing technique used to clean parts. It is important to be aware that each successive finishing step creates additional work and thus incurs additional costs. Clamping surfaces and an oversizing or undersizing allowance shall be provided at the design stage to facilitate post-production finishing, where desirable. Finishing steps can be performed only to a limited extent on filigree structures. Finishing steps can result in dimensional, form and positional deviations (e.g. rounding of corners and edges), which shall also be taken into account. Examples of post finish operations are: rotary polishing, infiltrating, die colouring, painting and metallization.

6.7 Design considerations

6.7.1 Allowing for powder removal

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

— reduce material consumption.

Cavities shall 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.

When designing cavities, channels or holes in polymer PBF parts, allowance shall be made for powder removal. The cavities contain loose, unsintered powder which can be removed post-production via dedicated openings, or left in place. Dedicated openings shall be provided for removing powder from areas that are difficult to reach, if powder removal was intended. Incorporating more than one access point can reduce powder removal effort and time. Blind holes and similar features shall be avoided whenever possible because it is very difficult to remove unsintered powder from them.

6.7.2 Reducing warpage

Warpage can affect large parts in polymer-based PBF. Thin-walled shells, long thin parts and large flat surfaces are particularly susceptible to warpage.

Various design measures can help counteract warpage, including

— reinforcement ribs,

— flowing transitions instead of abrupt wall thickness changes,

— self-supporting curved surfaces, and

— external auxiliary structures that are attached to the part during the build process but removed after manufacturing.

The orientation of the part in the build chamber can have a significant effect on warpage. To minimize warpage, position large flat surfaces vertically in the build chamber, rather than parallel to the build plane. If flat surfaces are positioned parallel to the build plane, position the surface with the tightest flatness requirements in the upward facing direction.

6.7.3 Wall thickness

The degree of fine resolution achievable with laser sintered polymers depends on the build direction. For this reason, it is important to orient the part appropriately within the build space. Lower wall thicknesses can be achieved parallel to the build plane (x–y plane) than perpendicular to it (x–z or y–z-axis). To avoid buckled or incompletely fabricated walls, minimum wall thicknesses are approximately 0,6 mm and 0,8 mm for thin walls built parallel to the build plane (x–y plane) and perpendicular to it (x–z or y–z plane). Thin walls and surfaces can be stabilized with reinforcement structures.

6.7.4 Gaps, cylinders and holes

The minimum realizable diameter of a hole or thickness of a gap depends on the depth of the gap, the thickness of the surrounding part, and its orientation in the build chamber. Smaller holes or gaps can be realized when they are oriented parallel to the build plane and when the surrounding part is thin (resulting in less oversintering and contraction of the holes or gaps). Anything smaller than a 1,5 mm hole can be difficult to fabricate accurately in polymer PBF, although holes as small as 0,6 mm to 0,8 mm can be fabricated when they are oriented parallel to the build plane and embedded in a very thin surrounding part (approximately 1 mm thick). Whenever the part geometry permits, cylinders shall be oriented orthogonally to the build plane. Cylinders that are parallel to the *x*–*y* build plane are susceptible to stair-stepping effects around their circumference. Cylinders as small as 0,8 mm in diameter can be fabricated accurately with polymer PBF[18].

6.7.5 Lattice structures

LB-PBF/P is very well suited to manufacture lattice structures. The geometry shall not be so thin as to compromise process reliability or prevent removal of loose powder if desired. With fine structures in particular it is important to pay careful attention to the stair-stepping effect associated with inclined surfaces. Lattice structures can also be used for reinforcing cavities, in which case the strut thickness of the lattice should be less than the wall thickness of the surrounding part.

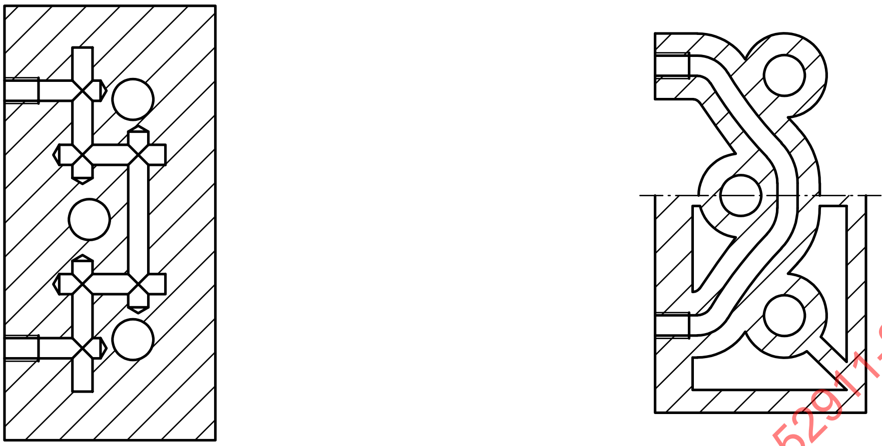
Typical LB-PBF/P machines can fabricate lattice struts down to almost 0,5 mm in diameter[18].

6.7.6 Fluid channels

In principle pressurized channels can be integrated into a part using LB-PBF/P. If the channel is intended to be pressurized, the wall shall be sufficiently thick to withstand the pressure as, due to the nature of the manufacturing process, the sintered material has some porosity, so pressure losses along the channels can be produced. Walls in PA 12 material are typically water tight for a thickness of at least 3 mm, although wall thickness can be reduced if some sealant is applied on the inner part to reduce this effect.

Other materials can require different wall thicknesses. In many cases, the channel geometry is matched to the fluid dynamics. The need to remove loose powder limits the complexity, length and minimum cross-section of channels. Above a certain cross-section, “wires” can be produced in the channel as a temporary support and subsequently removed to open up the channel. Inaccessible areas such as blind holes shall be avoided because they are difficult to clean.

An important factor for facilitating the removal of loose powder inside the channels can be reducing significantly the energy supplied to the material, which is also directly related to the diameter. Channels smaller than 5 mm are difficult to clean. Moreover, if the adjacent channel area has low thicknesses or even cavities with reinforcing structures, this prevents further heat accumulation in the area. Figure 4 shows how this can be achieved in design terms.



a) Poor

— Solid structure requires long build time, tends to warp, makes cleaning channels difficult.

— Angled channels difficult to clean.

— Blind holes encourage material to accumulate and hamper thorough cleaning.

b) Good

— Significant reduction in material consumption and build time.

— Easy cleaning with aerodynamic, continuous channel.

— Thin wall thicknesses for greater dimensional accuracy.

— Reinforcement (mesh structures) for stability.

SOURCE VDI 3405-3:2015.

Figure 4 — Examples of good and bad channel plate design (left, an unsuitable design, right, two better options)

6.7.7 Springs and elastic elements

The different materials available for LB-PBF/P offer various opportunities to create springs and elastic elements. Deformable elements shall not be held in a constant state of deformation since this results in permanent deformation due to stress relaxation of the materials.

The following elements can be produced.

— Classic spiral or leaf springs. They shall be designed in accordance with the properties of the sintered material and the build direction.

— Rubber-like damping elements can be created using elastomeric materials.

The stiffness of flexible materials can be influenced via the processing parameters. For materials such as elastomers, the material properties depend on processing parameters such as input energy density.

6.7.8 Connecting elements and fasteners

Connecting elements for laser sintered parts can be produced directly. With well-designed connecting elements, parts can often be joined together or separated without additional aids.

Examples of connecting elements include

— threads,

— hooks,

— eyes,

— dovetail,

— pins,

— snap-fit hooks (see Figure 5),

— tension locks,

— briefcase or handbag fasteners,

— screw caps, and

— push buttons.

The connecting elements listed above vary in terms of their complexity. Material-dependent gap dimensions often prove to be a limiting factor. It is generally better to fabricate fasteners/connectors in their open state since this allows for less bearing play in the fastener/connector. Ductility at the connection point can vary depending on the material and cross-section. The part will fracture or break if it is too brittle or the cross-section is not sufficiently flexible. Allowance shall be made for the fact that elongation at break varies depending on the build direction.

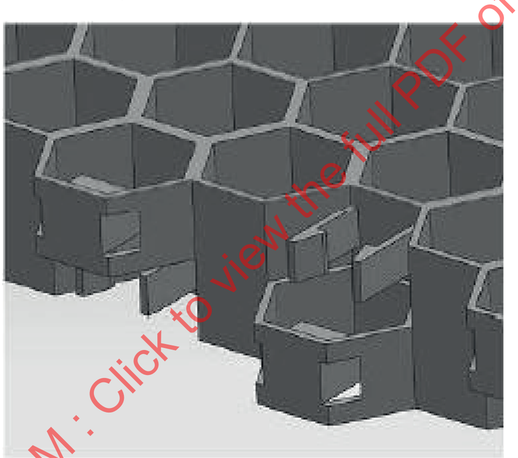


Figure 5 — Example of a snap-fit hook (courtesy of Fraunhofer IGCV, Augsburg, Germany)

6.7.9 Static assemblies

LB-PBF/P is an ideal manufacturing process for creating complete (fully assembled) assemblies. In the case of static assemblies, the procedure varies depending on whether the mechanical properties within the assembly are identical or not. In the first case, the irradiation parameters are the same, and in the second they are different.

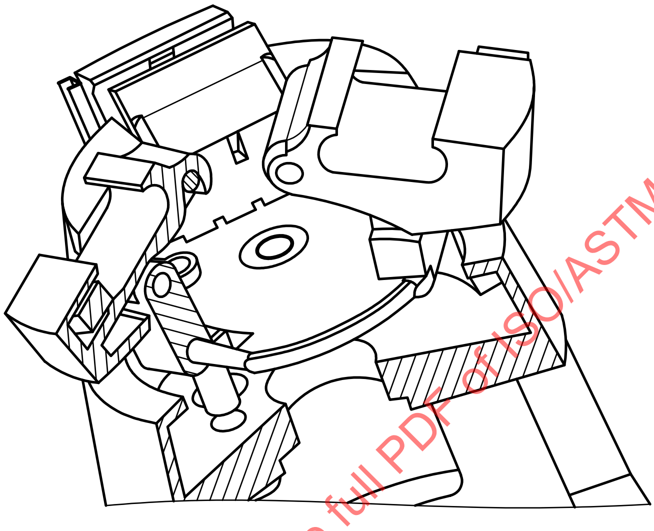
In this respect, the following points apply.

a) If all components of an assembly in the assembled state are fabricated using the same irradiation parameters, it can be helpful to merge existing modular components in the CAD to form one part. In this way, manufacturing defects caused by shared surfaces receiving a double dose of irradiation or similar can be avoided.

b) If different areas of a part are to have different material properties, i.e. different irradiation parameters are to be used, these individual elements shall be designed as individual parts and then correctly positioned in relation to one another during pre-production digital processing (as with multicomponent injection moulding). This allows different levels of stiffness to be achieved, for example.

6.7.10 Movable assemblies

(Sub-)assemblies can be created to save assembly time. This approach also allows parts to be produced which would otherwise be impossible to assemble. If individual sub-assemblies are intended to move relative to one another, a sufficiently large gap (for PA 12, this clearance should be about 1 mm, in some applications it may be less) is to be provided at their interfaces. Figure 6 shows a gripper that can be produced by LB-PBF/P as an example.



SOURCE VDI 3405-3:2015.

Figure 6 — Three-jaw gripper constructed as a movable assembly

6.7.11 Bearings

Slide and roller bearing functions can be created in areas of an assembly, which would be very costly to produce by conventional methods. A fully or partially integrated approach can be adopted, depending on the requirements for intended use, wear and force applied.

— With fully integrated roller bearings, the rolling elements (e.g. ball bearings) are created in the same build from the same material. Bearings produced in this way have considerable play and exhibit greater wear. These phenomena will be more complex with increasing stress on the rolling elements, so in most cases it is not advisable to manufacture the assembly in this way.

— With partially integrated roller bearings, the rolling elements (e.g. made from ceramic material) are inserted post-production. This approach produces a rolling element with less friction, greater mechanical strength and less play.

Both variants shall allow for subsequent powder removal through the provision of suitably sized cleaning openings and the avoidance of dead ends (blind holes) and similar design faults. With the partially integrated approach, the opening designed for inserting the rolling elements can also serve as the powder removal port. In this case, the opening shall be designed for easy access for subsequent insertion or replacement of rolling elements.

Ideally, radial bearings shall be created with their axes parallel to the build direction.

6.7.12 Joints

Joints can be integrated into a laser-sintered part without having to be assembled. The main points to bear in mind here are the greater friction between the moving elements, the greater clearance required by the manufacturing process and provision for powder removal. Fully enclosed joint sockets are difficult to produce and can be feasibly approximated by selective recesses in the surrounding contour (shell or socket).

Additional functions such as lock-in and stop positions can be created with the aid of integrated functional elements such as springs, grooves, pins and channels.

Film hinges (living hinges) are one piece components with no assembly needed, which can also be produced via LB-PBF/P. The life of the hinge can be increased and its functionality extended by adapting the shape, consistency, tapering (alternating wall thickness) and stiffening of the wall. A thickness of about 0,24 mm can be obtained for the hinges. They should be manufactured in the x–y plane allowing all the layers to work in the same way. In any case, the number of cycles to failure of these film hinges is lower than injection moulded versions.

6.7.13 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 shall 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[18].

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.

6.7.14 Cutting and joining

If parts are too large for the available build space, they shall be built in sections and subsequently joined. This means that the parts shall be divided into separate parts in the CAD file. The finished individual parts are then mechanically connected post-production. In its simplest form, separation can be achieved by cutting. However, it is advisable to produce a dovetail joint since this ensures that the parts are correctly aligned with one another and increases the strength of the joint. The joint itself is normally glued. Bolted connections or similar can also be provided to satisfy the mechanical requirements of the joint. It is important to design the joint with a cutting clearance (approximately 0,1 mm) between the two halves to facilitate joining and bonding. Furthermore, the joining points on the two parts shall be positioned in the same orientation and the same place in the build space where possible in order to minimize form and dimensional deviations. Figure 7 shows an example.

