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Additive manufacturing of metals — Finished part properties — Post- processing, inspection and testing of parts produced by powder bed fusion

Fabrication additive de métaux — Propriétés des pièces finies — Post-traitement, inspection et essais des pièces produites par fusion sur lit de poudre

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11

Email: copyright@iso.org
Website: www.iso.org

Published in Switzerland

ASTM International
100 Barr Harbor Drive, PO Box C700
West Conshohocken, PA 19428-2959, USA
Phone: +610 832 9634
Fax: +610 832 9635
Email: khooper@astm.org
Website: www.astm.org

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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 document 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 Committee F42, *Additive Manufacturing Technologies*, on the basis of a partnership agreement between ISO and ASTM International with the Objective 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).

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

As with conventional manufacturing processes (e.g. casting and milling), metallic parts produced by additive manufacturing technologies have critical-to-quality characteristics. These characteristics include density, strength, hardness, surface quality, dimensional accuracy, residual stresses, absence of cracks, voids, and structural homogeneity, which are typically tested in additively manufactured components. The quality of additively manufactured components is essential for functional components produced on an industrial scale. Thus, it is necessary to qualify additive manufacturing processes according to uniform criteria and to apply standardised in-process and post-process testing.

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Additive manufacturing of metals — Finished part properties — Post-processing, inspection and testing of parts produced by powder bed fusion

1 Scope

This document specifies requirements for the qualification, quality assurance and post processing for metal parts made by powder bed fusion.

This document specifies methods and procedures for testing and qualification of various characteristics of metallic parts made by additive manufacturing powder bed fusion processes, in accordance with ISO/ASTM 52927, categories H and M.

This document is intended to be used by part providers and/or customers of parts.

This document specifies qualification procedures where appropriate to meet defined quality levels.

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 3369:2006, *Impermeable sintered metal materials and hardmetals — Determination of density*

ISO 6892-1, *Metallic materials — Tensile testing — Part 1: Method of test at room temperature*

ISO 18265, *Metallic materials — Conversion of hardness values*

ISO 21920-1, *Geometrical product specifications (GPS) — Surface texture: Profile — Part 1: Indication of surface texture*

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

ISO/ASTM 52907, *Additive manufacturing — Feedstock materials — Methods to characterize metal powders*

ISO/ASTM 52920, *Additive manufacturing — Qualification principles — Requirements for industrial additive manufacturing processes and production sites*

ISO/ASTM 52927, *Additive manufacturing — General principles — Main characteristics and corresponding test methods¹⁾*

ISO/ASTM 52928, *Additive manufacturing — Feedstock materials — Powder life cycle management²⁾*

ISO/ASTM/TS 52930, *Additive manufacturing — Qualification principles — Installation, operation and performance (IQ/OQ/PQ) of PBF-LB equipment*

ANSI/ASME Y14.5, *Dimensioning and Tolerancing*

ASTM B311, *Standard Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity*

1) Under preparation. Stage at the time of publication: ISO/DIS 52927:2023.

2) Under preparation. Stage at the time of publication: ISO/DIS 52928:2023.

ASTM B962, *Standard Test Methods for Density of Compacted or Sintered Powder Metallurgy (PM) Products Using Archimedes' Principle*

ASTM E8/E8M, *Standard Test Methods for Tension Testing of Metallic Materials*

DIN 50125, *Testing of metallic materials — Tensile test pieces*

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

grain size

average grain size in the metallurgical structure when viewed in cross-section

4 Abbreviations

The abbreviations listed in [Table 2](#) are used throughout this document.

Table 2 — Abbreviations

AM	additive manufacturing
EDX	energy-dispersive X-ray spectroscopy
SEM	scanning electron microscope
CAD	computer aided design
NDT	non-destructive testing
QA	quality assurance
COC	certificate of conformance
ASL	approved supplier list
HIP	hot isostatic pressing
EDM	electrical discharge machining
PBF	powder bed fusion

5 Qualification

5.1 General

The manufacturer shall demonstrate the capability to produce AM parts to the requirements given in the purchase specification. The inspection and testing described in the following clauses are performed and assessed using the methods and acceptance criteria stated in the purchase specification.

NOTE Inspection and testing methods are specified at the design stage, as described in ISO/ASTM 52927, and are in accordance with the relevant standards and regulations that are required for the conformity of that part.

5.2 Part validation

Validation that the part produced complies with the requirements of the purchase specification shall be captured in a qualification record. A typical 'qualification record', shall consist of:

- technical documentation relating to part(s) produced;
- facility documentation;
- quality assurance (QA) documentation.

5.3 Technical documentation relating to part(s) produced

The technical documentation relating to part(s) produced shall contain:

- part specification in accordance with ISO/ASTM 52927, which includes inspection methods, associated plans, acceptance criteria, and representative quality indicators where applicable;
- feedstock specification, test results and declaration of conformity in accordance with ISO/ASTM 52907;
- material specification (consolidated product material properties specification);
- manufacturing plan (e.g. see ISO/ASTM 52904);
- records of destructive and non-destructive testing;
- inspection record for the part (in accordance with the purchase specification);
- other documentation required by the purchaser, regulation or product standard (e. g. material identification, labelling, product instructions).

NOTE 1 For some materials, there is a singular specification that controls both feedstock and material properties, such as metallurgical and mechanical properties.

NOTE 2 Technical specifications for metal powders are addressed in ISO /ASTM 52907.

5.4 Facility documentation

5.4.1 Additive manufacturer documentation requirements

Facility documentation requirements for industrial manufacturing sites are addressed in ISO/ASTM 52920.

For the purpose of this document, an outline of the relevant manufacturing plant and equipment shall be provided at the request of the buyer. The outline shall include the major items of equipment used for post processing, inspection, and testing (including details of geographical location).

The following facility documentation shall be provided:

- records of equipment qualification in accordance with ISO/ASTM TS 52930;
- records of powder lifecycle management in accordance with ISO/ASTM 52928.

The requirements in this subclause are met where a quality management system is in place (see [5.5](#)).

5.4.2 Subcontractor documentation requirements

Where the manufacturer subcontracts post-processing and/or testing activities, the manufacturer shall be able to indicate the conditions under which these activities are subcontracted and shall provide a purchase specification for the operations involved.

The manufacturer shall assess and approve the subcontractors for their capability to perform the subcontracted activity to the required quality level.

5.5 Quality assurance documentation

General QA documentation requirements are met by introducing a quality management system (e.g. ISO 9001 or ISO 13485).

Additive manufacturing QA documentation requirements shall be in accordance with ISO/ASTM 52920.

6 Post processing

6.1 General

Post-processing consists of activities performed after the completion of a build cycle but prior to final inspection activities.

NOTE Intermediate inspection can be performed between post-processing activities.

Post-processing operations are typically performed to achieve the desired material properties, final geometry and surface finish, and can include the following steps:

- post-build activities (e.g. cool down, declamping, removal from the AM machine, part cleaning);
- thermal treatment;
- separation from the build platform and support structures;
- surface finishing.

At the post-processing stage there are also several system-based operations performed (i.e. not related to the AM part) to prepare for subsequent builds. These activities are covered within other standards and include:

- recovery and reprocessing of unfused powder (in accordance with ISO/ASTM 52928);
- AM equipment cleaning and maintenance (in accordance with ISO/ASTM 52920).

6.2 Post-build activities

Following successful completion of the build, the chamber is allowed to cool and unfused powder is recovered from the build chamber. Once the build chamber is opened, the build platform fasteners can be removed, and care shall be taken to avoid deflection, which could induce cracking, due to the build-up of any residual stresses within the build. (see ASTM F3530-22)

Once the build assembly is removed from the AM machine, it can be cleaned and visually inspected (e.g. for imperfections, discolouration, separation from support structures). Loose powder that remains on the build assembly after exposure to atmosphere (i.e. no longer within an inert environment) can be removed by various methods (e.g. compressed gas, brushing, vacuum, sonic or ultrasonic cleaning methods). Loose powder removed at this stage shall be considered to be waste powder and disposed of safely.

For some non-reactive materials, loose powder that is removed within a controlled environment (e.g. glovebox, automatic depowdering unit), can also be reused where allowed by the manufacturer's procedures, subject to contamination and traceability controls.

6.3 Thermal treatment

6.3.1 General

Although it is not mandatory to apply any thermal treatment to additively manufactured parts, the following points should be considered.

NOTE Thermal treatment is executed after it is ensured that all powder located in internal channels is removed.

6.3.2 Reducing residual stresses

The build-up of successive layers with rapid heating and cooling generates residual stresses in the component, which can lead to distortion. Where used, support structures help to minimise this distortion by providing stiffness within the build assembly to resist deflection due to these residual stresses. Therefore, the build assembly is typically stress relieved prior to the removal of any support structures, although this is not mandatory. The release of thermal stresses can lead to distortion, over a short or prolonged period of time. Furthermore, local stress peaks can occur in the part, which can significantly reduce fatigue strength and lead to premature cracking. Stress-relief reduces stresses in the component in a controlled manner after manufacture, thereby preventing distortion.

6.3.3 Reducing anisotropy

The as-built part can exhibit anisotropy, which may be normalised to minimise the orientation and location dependence on the mechanical properties of the formed material and achieve the final mechanical property requirements.

NOTE ISO/ASTM 52909 includes supplementary guidelines for the evaluation of finished part properties, including orientation and location dependence, for metal parts produced by powder bed fusion.

6.3.4 Prepare material for mechanical post-processing

Processes such as annealing can reduce the hardness of the as-built material to facilitate subsequent machining operations. Annealing, followed by ageing, can reduce intergranular corrosion and cracking.

6.3.5 Densification

Hot isostatic pressing (HIP) can improve material properties through the reduction of porosity and anisotropy.

NOTE 1 ASTM A 1080/A 1080M provides a standard practice for hot isostatic pressing of steels, stainless steels and related alloys.

The thermal treatment specified depends on the material and desired mechanical properties, as defined within the material specification and agreed between manufacturer and purchaser.

NOTE 2 ASTM F 3301a includes details of thermal treatments for various metals produced by powder bed fusion.

Test specimens used for destructive testing shall be representative of the part and therefore be subjected to the same thermal post-processing operations as the part they represent.

6.3.6 Annealing and aging

Annealing, followed by ageing, can also enable grain boundary carbides to enter into solution and thus prevent unacceptable grain boundary carbide precipitation, which can lead to intergranular corrosion and cracking.

6.4 Separation from the built platform and support structures

Various items can be present within the build assembly, which require separation from the build platform, from support structure and/or from other items (e.g. the part, test specimens). A suitable method of separation shall be specified in the manufacturing plan, such that separation does not have a detrimental effect on the integrity of the part or test specimens, e.g. wire EDM, metallographic saw, breaking parts off by hand.

Separation from the build platform should be studied to determine the best method and when to be performed (see 6.3.2).

6.5 Surface finishing

6.5.1 Surface finishing operations

Suitable finishing operations may be selected by the manufacturer and shall be defined within the manufacturing plan, to achieve the final geometry and surface finish requirements, specified in the design.

NOTE Numerous finishing operations are available, examples of which are listed below:

- machining (e.g. turning, drilling, milling);
- electrical discharge machining (EDM);
- abrasive operations (e.g. grinding, polishing, vibratory finishing, abrasive slurries);
- blasting operations (e.g. sand blasting, shot peening);
- chemical finishing (e.g. plating, dipping, degreasing);
- coating (e.g. painting, spraying, powder coating).

The selection depends upon the material, geometry (e.g. size, complexity, accessibility), surface finish (e.g. roughness, waviness, lay), tolerances, aesthetic and economic considerations.

6.5.2 Machining allowances

Depending on the requirements of an additively manufactured part, it may be necessary to machine one or several areas to comply with the required tolerances. This typically requires a machining allowance which comprises at least the maximum possible dimensional deviation.

Machining allowances are to be regarded as a “cutting allowance”, i.e. for machining solids of revolution or for two-sided machining, allowances shall be applied twice in accordance with ISO 21920-1 or ANSI/ASME Y14.5.

Consideration should also be given to the fact that, depending on the geometry, additively manufactured parts may be subject to warpage. An additional machining allowance may be required for this (see ASTM F3530-22).

7 Inspection and testing

7.1 General

The following aspects may be controlled and documented for quality assurance purposes (e.g. through controlled procedures and records):

- metallurgical testing;
- mechanical testing;

- surface quality inspection;
- geometrical inspection (form, dimension and tolerances);
- non-destructive testing.

NOTE Additional records, not covered in this document:

- machine build log report, see ISO/ASTM 52904;
- powder cycle/reconditioning, see ISO/ASTM 52928;
- equipment maintenance records, see ISO/ASTM TS 52930;
- cleaning lenses/building chamber → quality specification, see ISO/ASTM TS 52930;
- filter (quality, saturation, condensate), see ISO/ASTM TS 52930;
- in-process monitoring (melt pool analysis, etc.), see ISO/ASTM 52920.

7.2 Metallurgical testing

7.2.1 Objective

Numerous methods have been developed in metallography to quantitatively and/or qualitatively describe structural characteristics in metallic materials, including defects such as pores and cracks. These can equally be applied to the analysis of test specimens and parts made by PBF to provide information about manufacturing quality, material characteristics and behaviour. The structure of a material is characterised by the type, size, shape, distribution and orientation of the structural components. Numerous metallographic investigations can be carried out by examining the structure of a polished cross-section of a test specimen or appropriately prepared part with the naked eye, a magnifying glass or a microscope. While general metallographic procedures described in other standards are typically sufficient for the preparation of metals produced in laser powder bed fusion, there are structures and features specific to this production method that occur frequently enough to be of note.

7.2.2 Test specimen selection, design, and preparation for part characterization

Metallographic characterization of parts produced by powder bed fusion is a common operation, but there are process and material details that may not be immediately apparent to new users of the technology. The two fundamental test specimen types that are commonly processed are those cut from actual parts and those specifically designed to be used for metallographic evaluation.

In the case of test specimens cut from actual parts, a typical goal is to ensure that the test specimen is free from defects. In the powder bed fusion process, material is formed at the same time as the part, and an approach akin to that taken in the characterization of cast materials is required, as opposed to the approach taken in subtractive manufacturing processes where the material properties are already known. Care shall be taken because many imperfections depend on the specific geometry that is produced, so it can be difficult to extrapolate material quality characteristics from simple test specimens to complex parts, even when using the same powder and build parameters. For the purposes of sectioning the part, the use of either metallographic saws or wire EDM is recommended over machining, to ensure that the material is not adversely affected during sectioning. This is of particular concern with softer materials.

The second case of processing parts designed for metallographic characterization allows for substantial freedom to design the part to fit the need and ease the process of test specimen preparation. A few considerations for the design of the test specimen geometry are listed in the following:

- a) Test specimen size: The test specimen should be sized appropriately to fit in the metallographic mounting cup or mould or planned to be sectioned so that it will fit. Again, when possible, the parts

should be sectioned using a method that does not adversely affect the material. Metallographic saws or wire EDM are commonly used for this purpose.

- b) Location: If the test specimen is cut out of a part, the location should be defined in a drawing of the part and added to the documentation in the test report.
- c) Polished face orientation: The polished face of the part may be in a plane parallel to the build platform (XY), or in a plane parallel with the build direction (Z), which are often of great importance for the types of structures that are visible in the test specimen. For the characterization of some effects, it can be beneficial to introduce a feature in the part to indicate the orientation of the part within the XY plane as well.

The plane of polishing shall be specified in the quality control plan for the part. If no direction is specified, then both directions should be evaluated.

- d) Surface effects: Often the external surfaces of parts produced in laser powder bed fusion parts are not representative of the bulk, internal material. Observation of this surface region can or cannot be the goal of the characterization effort, but users should be aware that characterization efforts in near surface regions are subject to these effects.
- e) Mounting method: If mounting fine structures, such as lattices or parts with thin walls, hot mounting is not recommended as the pressure that is used during the mounting process can substantially deform the part.
- f) Labelling: In the case where a number of test specimens from a single build is cut, mounted and polished, it can be beneficial to label directly into the part such that labels are visible during subsequent steps.
- g) Required material response: For example, a part that is used for the characterization of bulk material density cannot be well suited to determining the level of near surface porosity. It is recommended to consider the required material response.
- h) Thermal treatment: It may be desired to perform thermal post-processing (see [6.3](#)) in addition to mechanical post-processing. Test specimens shall be subjected to the same post-processing as the parts they represent.

The test specimen shall be prepared in accordance with a standard specified (e.g. ASTM E3). After the test specimen is mounted using either a hot mount press or cold mount mould, it is typical to grind and then polish the test specimen.

After fine polishing, there are several possible subsequent steps. This is the ideal time to measure bulk porosity in the test specimen by taking a digital photo and processing the image to determine the relative density, as described in [7.2.3](#). After this analysis, the test specimen may be chemically etched to show additional structure and permit a more detailed examination of the metallic structure in PBF. In most of the cases etching is required to reveal the separate microstructural constituents of a metal alloy. Various etching techniques exploit the diversity of individual types of grain, e.g. crystallographic orientation, chemical composition, hardness, chemical resistance. A wide variety of etching techniques can be used on metallographic specimens.

In certain materials, etching in the as-build condition also exposes features unique to materials produced by powder bed laser fusion. It is often possible to see evidence of each pass of the laser over the material. In these materials, it is often possible to see the path of both the bulk scan and the contour scan, which can be beneficial when diagnosing porosity problems due to insufficient overlap between those scans.

7.2.3 Test methods, parameters, and test specimens

Refer to ISO/ASTM 52927 for examples of suitable test methods, parameters, and test specimens.

7.2.4 Chemical analysis

The chemical composition shall be determined using methods stipulated in the material specification.

7.2.5 Metallurgical properties

The grain size shall be measured in at least two orthogonal planes (e.g. horizontal and vertical planes relative to the build direction) because of the potential for microstructure anisotropy.

7.2.6 Determining the non-metallic inclusion content

Non-metallic inclusion content shall be assessed using a method appropriate for the selected material (see ISO/ASTM 52927 and the relevant material specification).

7.2.7 Analysis and test report

When analysing metallographic specimens, it is important to be aware of the micro-structural characteristics created by the layer-on-layer construction process of metal parts made by PBF. The test report shall contain at least the following information:

- reference to the applied standards;
- specimen type;
- specimen identification;
- material;
- any special remarks, e.g. thermal treatment;
- test conditions;
- orientation of specimen in the build space;
- relative location of specimen in the build space;
- test specimen (derived from part) or sample;
- results of the analysis (in accordance with the test standard);
- if a specific microstructure is required to be present in any specified location in the part, a metallographic specimen shall be removed from that location, which location shall be illustrated in the report. Any etchant used to reveal the specimen microstructure shall be identified in the written portion of the report;
- other information required by the selected test standard.

7.3 Material testing

7.3.1 General

Appropriate test methods shall be selected, and specified in the manufacturing plan, to determine the mechanical properties required by the material specification.

NOTE Refer to ISO/ASTM 52927 for examples of suitable test methods.

7.3.2 Orientation in the build space

Test specimens shall be located and oriented within the representative build envelope, including the worst-case condition (i.e. location/orientation), to characterize the process and assess the risk of mechanical variation within the build envelope.

NOTE 1 ISO/ASTM 52911 (series) provides technical design guidelines for positioning in the build space, with consideration of orientation with respect to the build platform and the recoater.

NOTE 2 ISO/ASTM 52921 provides standard practice for part positioning, coordinates and orientation.

7.3.3 Test specimen geometry and surface quality

Test specimen geometry and surface quality are defined in the standard for the test.

NOTE Examples of geometric test pieces are available in ISO/ASTM 52902.

7.3.4 Density (part)

The relative density of parts produced by powder bed fusion is typically at least 99,8 % of the theoretical material density.

Density can be tested by Archimedean methods, by gas pycnometry (see ISO 12154) or optically by quantitative analysis of metallographic specimen images. Non-destructive testing methods can also be used for density evaluation via image processing of 2D or 3D images (see [7.3.6](#)).

Archimedean methods are typically faster and provide information about overall porosity, whilst image analysis methods yield more information about the type and distribution of porosities within a single plane or in a volume. Archimedean methods are typically used to determine density in the early phases of metallographic qualification testing. Determining density purely by gravimetric means (i.e. using measurements to calculate the volume and weighing a specimen) is not considered to be sufficiently accurate.

[Figure 1](#) shows a typical analysis via image analysis method of the microstructures of test specimens with a density greater than 99 %. and [Figure 2](#) shows a density of less than 99 %.



Figure 1 — Light micrograph of the micro-section (unetched) of 316L grade steel with a density of more than 99 %

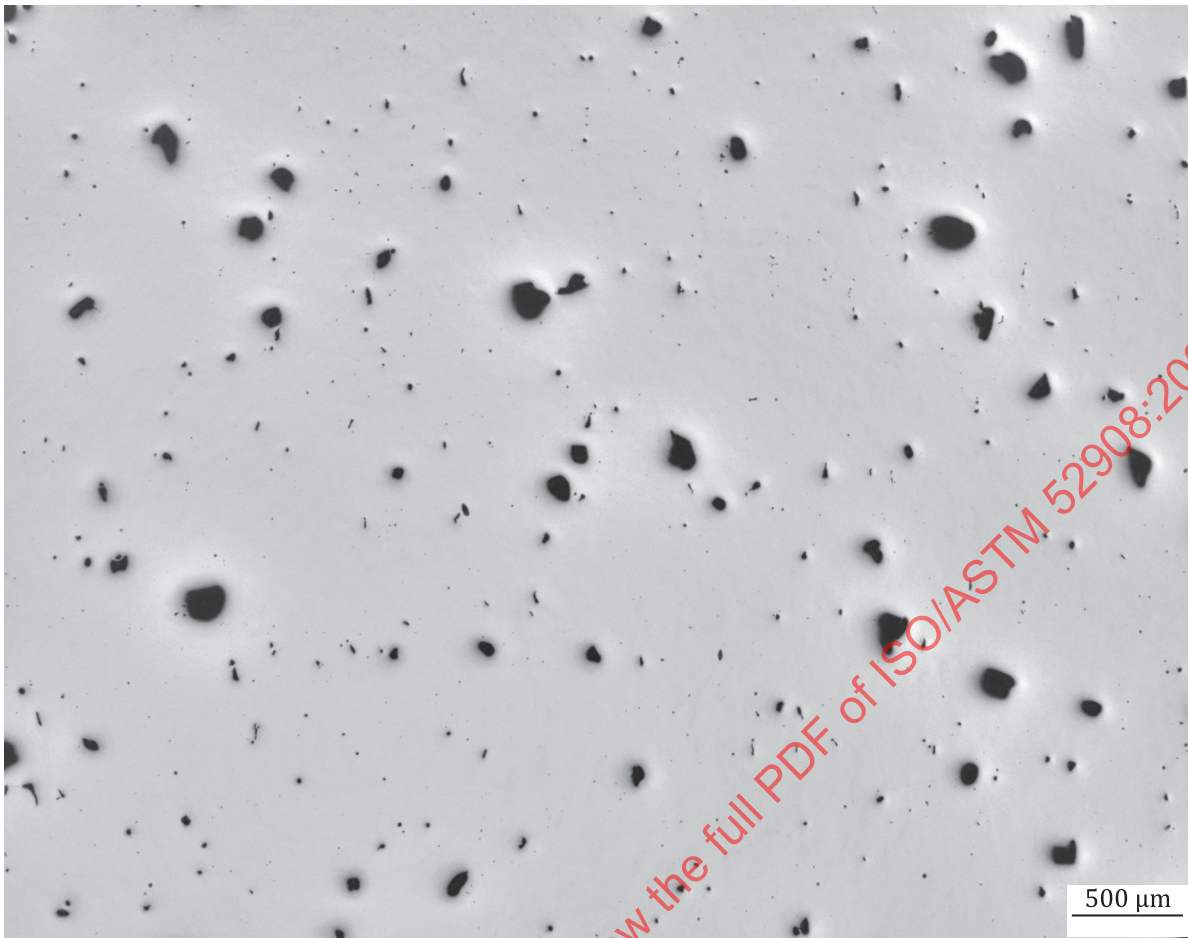


Figure 2 — Light micrograph of the micro-section (unetched) of 316L grade steel with a density of less than 99 %

7.3.5 Archimedeian method

7.3.5.1 Objective

To determine density by the Archimedeian method, a part is weighed in air initially, and then in liquid. The advantage of this method compared with apparent solid density determination by quantitative structural analysis is that results can be obtained with comparative ease and cover the entire volume range of the part or specimen. The disadvantage is that this method only determines the density. It provides no information about the type, distribution and shape of structural porosities.

7.3.5.2 Test methods, parameters, and test specimens

Density shall be determined in accordance with the procedure described in ISO 3369, ASTM B962 or ASTM B311. For test specimens with relative densities less than 98 %, ASTM B963 may be used.

7.3.5.3 Test specimen preparation

ISO 3369 stipulates a test specimen volume of more than 0,5 cm³. Thus, an optimal compromise between cost-effective test specimen production, ease of handling, measurement accuracy and information value of the microstructure is needed. Cube-shaped test specimens which retain an edge length of 10 mm after separation from the build platform are recommended. According to the standard, test specimen surfaces shall be cleaned. It is also advisable to completely remove any surface roughness caused by processing by machining to avoid measurement errors for weighing in liquid caused by air bubbles

adhering to the test specimen. It is also permissible to use a mild surfactant to minimize adhesion of bubbles when a machined or improved surface finish is not possible.

7.3.5.4 Analysis and test report

Density determination shall be conducted and reported in accordance with ISO 3369:2006, Clause 8.

7.3.6 Image analysis of metallographic specimens

7.3.6.1 Objective

Determining density by porosity analysis as part of the quantitative microstructural analysis permits comparative determination of the relative density of a test specimen, especially if test specimens always go through the individual stages in the same way. Compared with density determination by the Archimedean principle, the main advantage of using micrographs obtained by optical and electron microscopy and subsequent image processing is that other quality characteristics apart from relative density can be identified, such as size, shape or pore distribution, as well as defects such as bonding faults or cracks (see [Figure 3](#) and [Figure 4](#)).

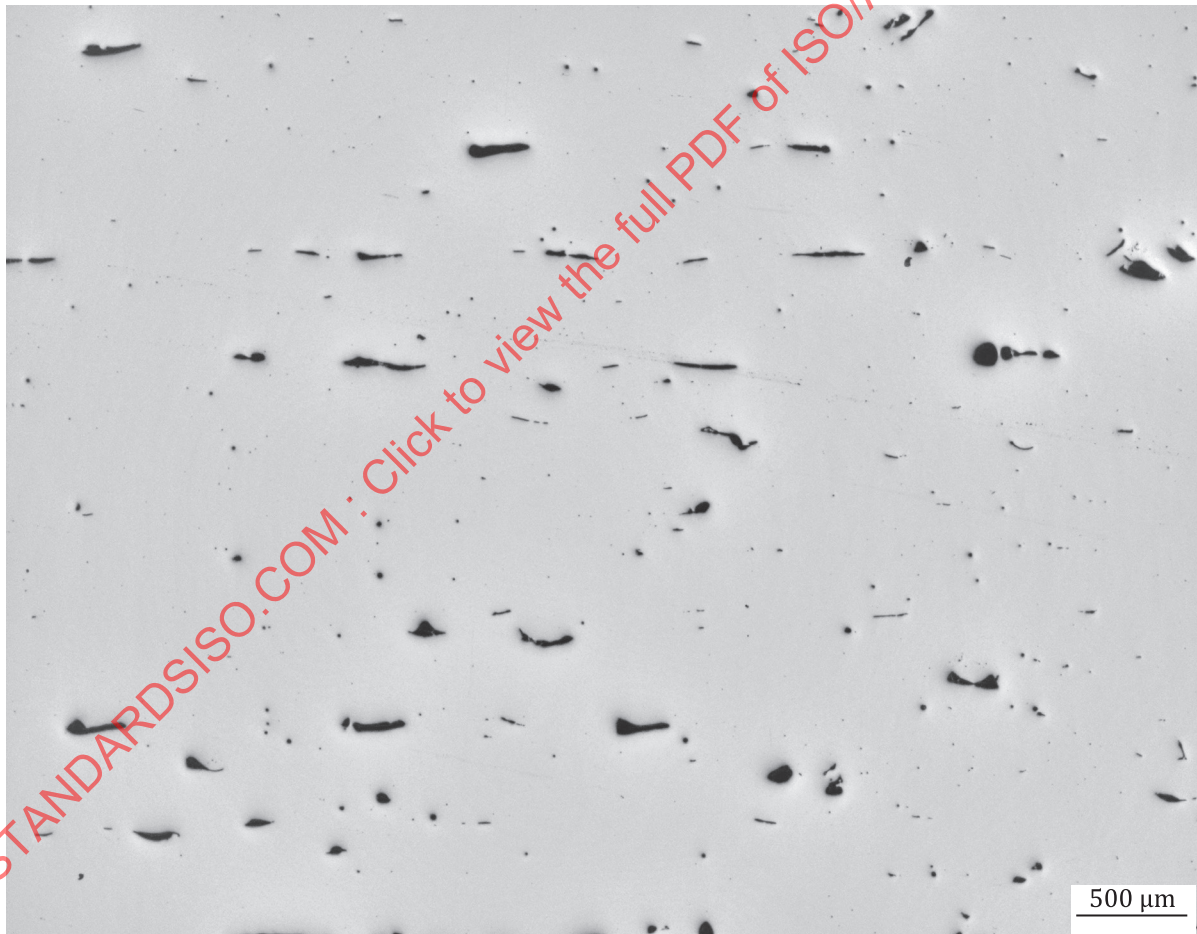


Figure 3 — Light micrograph of the micro-section (unetched) of 316L grade steel with embedded pores



Figure 4 — Light micrograph of the micro-section (etched) of 316L grade steel

7.3.6.2 Density, test methods, parameters, and test specimens

To determine density with the aid of micrographs, test specimens shall be prepared as described in ISO 3369:2006, Clause 6.

The prepared surfaces are photographed in the light microscope. Magnification shall be selected to ensure that relevant features such as pore shape and size are well-reproduced and at the same time a sufficiently large analytical area is available for statistical analysis which is representative of the pore distribution.

At least five images of the prepared surface shall be taken at predefined positions distributed across the metallographic specimen. Since the pore structure can be anisotropic, sections in a variety of parallel and non-parallel planes should be examined.

NOTE 1 Determining the density of metal parts made by PBF using prepared micrographs relies solely on the predetermined positions on the specimen or part. The density of the test specimen material is thus based only on a comparatively small area of the micrograph(s) relative to the total volume of the specimen. Pores which are not captured in the micrograph are excluded from the porosity determination. Consequently, it is possible that individual, localised, large-volume pores are not included in the porosity determination and the results obtained are misleading.

For the reasons described in Note 1, it is recommended to use a combination of the two test methods described (Archimedean method and image analysis) to determine the density.

NOTE 2 ISO/ASTM 52927 provides a list of standards and test-methods, for example ISO 643.

7.3.6.3 Analysis

Digital image processing is used to prepare the images prior to surface analysis. To determine density and porosity, the images are binarized, which means that each pixel in the image is assigned either to the material or to a pore. The ratio of pixels in the material or pores relative to the total number of pixels in this image represents the relative density or porosity, since the percentage area is equal to the percentage volume of this structural characteristic in the test specimen.

The arithmetic mean of all the images of one analytical area shall be calculated to obtain a representative statement. The mean value is usually expressed as a percentage.

The position of the analytical plane in relation to the direction in which the re-coating is applied and the layers are built up should also be indicated.

NOTE The discrimination of matter from pore using any image processing software depends on the image threshold (contrast, brightness) value selected by the operator. The greater this threshold value, the greater both the measured porosity and pore size. This problem can be resolved if this threshold value is adjusted so that the image-processing-measured porosity becomes equal to that obtained with the independent Archimedean method.

7.4 Mechanical testing

7.4.1 Static testing

7.4.1.1 Tensile test

7.4.1.1.1 Objective

The tensile test is used to assess the strength and deformation behaviour of additively manufactured metal parts by recording static material characteristics in a torque-free state under monotonically increasing tension. The tensile test for metal material properties determination, at room temperature, shall be performed in accordance with ISO 6892-1 or ASTM E8/E8M. The tensile test at higher or lower temperatures should be performed using the following standards:

- ISO 6892-2, ISO 6892-3;
- ASTM E 21, ASTM E 1450.

Shapes, dimensions, and designations of tensile test specimens to facilitate the production of standardised tensile specimens are available in various standards, depending upon the material and application (e.g. DIN 50125; ASTM E8/E8M; ISO 2740).

Test specimen preparation for tensile testing can be found in ISO 377.

For orientation and location dependence of mechanical properties for metal powder bed fusion, as well as the machining of test specimen from actual parts, see ISO/ASTM 52909.

All listed tests and test specimen shapes are intended as examples of recommended practices. The exact test specimen shape, the test design and the test procedure shall be agreed in close consultation with the inspection body.

7.4.1.1.2 Test methods, parameters, and test specimens

During the tensile test, the test specimen is subjected to uniaxial tension at a predetermined and constant test speed, generally until failure, to determine one or several defined mechanical characteristics. The tensile result shall be recorded as per the applicable test standard used.

7.4.1.1.3 Test specimen shape, dimensions, and designation

Test specimen shape, dimensions and designation shall comply with ISO 6892-1, ASTM E8/E8M or DIN 50125, unless other rules are required by the particular industry or application. Use test specimen applicable for the manufactured part. It is up to the manufacturer to specify the type used. Test specimens with “as built” surface condition are allowed, but the specimen surface condition has to be stated in the text report.

It is preferable to choose an adequate test specimen size for process monitoring purposes while minimizing additive manufacturing time and costs. This aspect is important in view of the frequent testing of processes and materials and the large number of test specimens needed to record the required characteristic values with sufficient statistical reliability (see e.g. ASTM F3001, ASTM 2924, ASTM F3302, 15.1 and 15.1.1). At least three workable results per orientation within the build space are required to obtain statistically robust measurement results (in terms of reproducibility and comparability).

Where retesting is permitted by the standard, additional test specimens may be included within the build layout to accommodate this retesting and potentially avoid rework.

If the characteristics are necessary for the qualification of the machine, ISO/ASTM TS 52930 for equipment qualification should be applied.

Where equipment qualification (i.e. in accordance with ISO/ASTM TS 52930) shows variation of material properties at specific locations within the build space due to multi-laser systems, the manufacturer shall include additional specimens in these regions to assess this risk.

7.4.1.1.4 Test specimen identification

All test specimens shall be labelled to prevent any possible mix-up during the entire processing and testing process and build position recorded.

7.4.1.1.5 Analysis and test report

The test report shall include all relevant characteristic values and test parameters, as stated within the selected standard, but at least contain the following information:

- test specimen identification;
- material;
- test specimen type;
- reference to this document and other applicable standards;
- the method used;
- orientation and position of the test specimen in the build space;
- test results including a reference to the clause which explains how the results were calculated;
- any deviations from the procedure;
- any unusual features observed;
- the date of the test.

7.4.1.2 Hardness

7.4.1.2.1 Objective

The tests listed in ISO/ASTM 52927:—, Table A.6 serve to determine and record the hardness of additively manufactured metal parts.

All suggested tests and specimen shapes are recommendations. The exact specimen shape, the test design and the test procedure should be defined in close consultation with the inspection body.

7.4.1.2.2 Test methods, parameters, and test specimens

Since hardness measurement which under certain circumstances (in accordance with the aforementioned standards) can be applied to the actual component, the specimen shape is not defined for any of the tests.

The test specimens' surface shall be designed and prepared to permit accurate measurement of the impression left behind by the indenter. The results and their distribution are influenced by the surface finish.

A minimum test specimen thickness is recommended due to material displacement caused by penetration of the indenter. The specimen surface is required to be smooth, flat and grease-free for all of the test methods.

Minimum distances between the indentations and the edge of the specimen shall be maintained to avoid mutual interference. These minimum distances are stated in the standards for the hardness test methods.

7.4.1.2.3 Specimen preparation

To assess the anisotropic material characteristics of parts produced in PBF (powder bed fusion), it is advisable to make cube-shaped specimens e.g. cubes with an edge length of 10 mm. Measurements are taken in the structural core at a distance of 1 mm to 2 mm from each surface

- parallel to the construction plane and
- perpendicular to the construction plane.

7.4.1.2.4 Analysis and test report

The standards listed in ISO/ASTM 52927:—, Table A.6 describe how to analyse the test results. Measurements are expressed in accordance with the test method, as described in the relevant standards.

It is recommended, if not otherwise specified in related standards, that five hardness measurements are recorded per surface, eliminating the highest and lowest measurement in each case, and giving the mean of the remaining three measurements as the final value.

The conversion of hardness numbers between the different test methods is specified in ISO 18265.

7.4.1.3 Impact test

7.4.1.3.1 Objective

Impact testing serves to assess the resistance to impact stress (impact strength) of material in PBF.

The tests listed in ISO/ASTM 52927:—, A.7.4, serve to determine and record the impact strength of additively manufactured metal parts.

The material characteristics obtained from the impact test are the absorbed energy (the impact energy required to break the notched bar) KV or KU from which the transition temperature and the fracture behaviour of the material can be determined.

NOTE Although indicating the impact energy has no direct application for evaluating the component, it provides an important qualitative assessment of the material characteristics of actual components with notches, cavities, cracks, etc. in the event of over-stressing and subsequent failure. For this reason, the impact test is used in addition to testing susceptibility to brittle fracture of metallic materials to inspect the quality and consistency of microstructure and treatment conditions and to investigate signs of ageing.

7.4.1.3.2 Test methods, and test specimens

Care shall be taken to ensure that the specimen temperature is appropriate for the application. The transition temperature should be determined using the same test procedure as that used for nonlaser-generated test specimens.

Test specimen geometry shall be as defined in the selected standard.

Where surface requirements are specified, a machining allowance shall be provided on all sides of the test specimen during design and notches should be produced during post-processing. Where test specimens with “as built” surface condition are specified, the test specimen surface condition shall be declared within the test-report.

The orientation of the impact specimen within the build-space, and subsequent direction and location of the notch, shall be specified to test the most demanding condition.

7.4.1.3.3 Test specimen preparation

The notched bars are positioned in the build space in the same way as specimens for the tensile test (voir [7.4.1.1](#)).

Prior to testing, notched-bar test specimens should undergo heat treatment to achieve the characteristic microstructure of the intended application. The testing of laser-generated notched-bar test specimens without preliminary heat treatment (manufacturing condition) is recommended only within limits for determining material behaviour due to the microstructure conferred on the material by the process.

Where test specimens with “as built” surface condition are specified, the test specimen surface condition shall be declared within the test report.

7.4.1.3.4 Analysis and test report

Assessment of material toughness should include the microscopic fracture appearance and bending angle as well as the numerical value for notch impact energy. The ratio of brittle fracture to fracture area is used to quantitatively assess the fracture appearance. During analysis, it is important to be aware of the micro-structural characteristics created by the layer-on-layer building process.

The test report shall include all relevant characteristic values and test parameters, as stated within the selected standard, but at least contain the following information:

- test specimen identification;
- material;
- test specimen type;
- reference to this and other applicable standards;
- orientation and position of the test specimen in the build space;
- test results including a reference to the clause which explains how the results were calculated;
- any deviation from the procedure;

- any unusual features observed;
- the date of the test.

7.4.1.4 Bend test

7.4.1.4.1 Objective

The objective of this test method is to assess the plastic deformation of additively manufactured metal parts.

The tests listed in ISO/ASTM 52927:—, Table A.5, serve to determine the performance of the material when subjected to plastic deformation during bending, and record the test result from the method selected.

The bend test described below is intended as a recommendation for the test specimen shape and test performance for flat products made by PBF. All suggested tests and test specimen shapes are intended as examples of recommended practices. The test specimen shape, the test design and the test procedure shall be agreed on in close consultation with the inspection body.

7.4.1.4.2 Test methods, parameters, and test specimens

The bend test specimen is subjected to an increasing load at the prescribed constant test speed until a specific bending angle is obtained, without altering the loading direction. The force and travel distance displacement (traverse distance) shall be recorded.

Before performing the bend test, it is important to first verify that a suitable bending device is available for testing additively manufactured metal test specimens. The hardness of the punch and rollers shall be selected according to the specimen thickness and strength to avoid deforming the punch.

The bending test specimens shall not be bent prior to the test. The suitably prepared bending test specimen is inserted into the bending device so that any burrs are located on the inside, facing away from tensile stresses. It is important to ensure that cracking is not initiated from the edges during the bend test. This can be ensured by appropriately finishing the edges according to the material.

7.4.1.4.3 Test specimen preparation

Test specimens are produced in the same way as test specimens for the static tensile test.

The surface finish of bending specimens should be consistent with their end-use. After finishing, powder residues and beads shall be removed from the test specimens. It is important to avoid damaging the surface. The test specimen surface shall be crack- and notch-free over the entire test length.

An identification mark shall be applied to the compressively stressed top side. It shall be placed in a way that it can still be read after test completion.

At least five workable test specimens per orientation within the build space are required to obtain statistically reliable measurement results (in terms of reproducibility and comparability).

7.4.1.4.4 Analysis and test report

The test results shall be recorded and analysed according to selected test method.

The test report shall include all relevant characteristic values and test parameters, as stated within the selected standard, but at least contain the following information:

- test specimen identification;
- material;