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Additive manufacturing — Test artifacts — Geometric capability assessment of additive manufacturing systems

Fabrication additive — Pièces types d'essai — Évaluation de la capacité géométrique des systèmes de fabrication additive

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

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

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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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

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 ISO/TC 261, *Additive manufacturing*, in cooperation with ASTM Committee F42, *Additive Manufacturing Technologies*, on the basis of a partnership agreement between ISO and ASTM International with the aim to create a common set of ISO/ASTM standards on additive manufacturing.

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.

Additive manufacturing — Test artifacts — Geometric capability assessment of additive manufacturing systems

1 Scope

This document covers the general description of benchmarking test piece geometries along with quantitative and qualitative measurements to be taken on the benchmarking test piece(s) to assess the performance of additive manufacturing (AM) systems.

This performance assessment can serve the following two purposes:

— AM system capability evaluation;

— AM system calibration.

The benchmarking test piece(s) is (are) primarily used to quantitatively assess the geometric performance of an AM system. This document describes a suite of test geometries, each designed to investigate one or more specific performance metrics and several example configurations of these geometries into test piece(s). It prescribes quantities and qualities of the test geometries to be measured but does not dictate specific measurement methods. Various user applications can require various grades of performance. This document discusses examples of feature configurations, as well as measurement uncertainty requirements, to demonstrate low and high grade examination and performance. This document does not discuss a specific procedure or machine settings for manufacturing a test piece, which are covered by ASTM F 2971 and other relevant process specific specifications.

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*

ISO/ASTM 52921, *Standard terminology for additive manufacturing — Coordinate systems and test methodologies*

ASME B46.1, *Surface Texture (Surface Roughness, Waviness and Lay)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/ASTM 52900 and ISO/ASTM 52921 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/

4 Significance and use

4.1 General

Measurements and observations described in this document are used to assess the performance of an AM system with a given system set-up and process parameters, in combination with a specific feedstock material.

The primary characterization of the AM system obtained by this document is via geometric accuracy, surface finish and minimum feature sizes of the benchmarking test piece(s).

4.2 Comparing results from one machine

The test piece(s) can be built and measured for example when the new machine is installed. The test piece(s) may be used to periodically evaluate the performance or diagnose a fault in one AM system, for example, after system maintenance or as defined by the requirements of a quality system.

The test piece(s) described in this test method may be used as a demonstration of capabilities for a contract between a buyer and seller of AM parts or AM systems.

Data from the measurements described in this document can be used to gauge the impact of new process parameters or material on the AM system performance.

Certain test geometries may be included with every build on a particular AM system to help establish performance traceability. Depending on the needs of the end user, not all test artifacts need to be built, and individual test artifacts can be built separately if required.

5 General principles for producing artifacts

5.1 General

This clause outlines principles applicable for producing all of the test artifact geometries in this document. Reporting requirements are previewed in connection with the production steps in this clause, but more details about recording and reporting can be found with the individual artifact descriptions given in Clause 7.

5.2 Need to use feedstock conforming to a material specification

In order to ensure repeatable results, the use of a quality feedstock material is needed. A feedstock material specification should be selected or determined by the end user and the feedstock used for test artifact trials should match said specification. For example, the specification may include the particulate properties (particle size, size distribution, morphology) for powder feedstock, bulk properties (such as flow) and chemical properties (such as chemical composition and level of contamination). Although the details of the material specification shall not be disclosed (unless otherwise agreed between supplier and purchaser), it should be documented by the producer and reported with a unique alphanumeric designation as specified by ASTM F2971:2013, Annex A1, element "B". For powder-based processes, the material specification should specifically address limitations of powder re-use and percent of virgin/re-used powder.

5.3 Need to undertake artifact building according to a documented process specification

The processing of the material in the AM system should be undertaken according to a documented process specification/manufacturing plan, as specified by ASTM F2971:2013, Annex A1, element "C". This may be a proprietary internal standard or external standard (subject to buyer/seller negotiations), but the producer should document user-definable settings and conditions surrounding the building of parts. For example, it should document the layer thickness, build strategies (e.g. scan path, tool path, and/or scan parameters), temperatures, etc. used during the build. This process should be consistent for all test artifacts produced within one build. These recommendations can be different for each use, so the parameters in the process specification should be agreed between the vendor and end user.

5.4 File formats and preparation

The file formats used and steps of the digital file preparation including slice parameters should be included in the process specification. Care shall be taken during the creation and transfer of data files to avoid degradation of the model. Any discrepancy between these affects the outcome of tests on the artifacts and for this reason, best practice for the control of the file formats and preparation is discussed here.

5.5 Download files

The 3D digital models for standard test artifact geometries can be downloaded in *.step format at https://standards.iso.org/iso/52902/ed-1/en. For a complete list of available files, please see Annex D.

5.6 Discussion of file conversion

When a CAD model is converted to AMF, STL (or any intermediate file format), sufficient fidelity shall be maintained to ensure that the test artifact produced from it fairly reflects the capabilities of the AM system under assessment. The file conversion tolerance selected should ensure that the maximum deviation of the data from the nominal CAD model is less than one quarter and, based on good measurement practice, ideally less than one tenth of the expected accuracy of the AM system being assessed. Currently, most additive manufacturing equipment cannot produce features with a resolution better than 10 µm, therefore CAD models are saved to STL/AMF ensuring at least a 2,5 µm accuracy or better. This is only general guidance and should be confirmed for the specific output system. It is recommended that users check the maximum deviation and record the conversion parameters used, as well as any maximum deviation (chord height and angular tolerance).

Files should not be scaled up or down either during conversion or afterward. Machine correction factors (e.g. offsets, axis scaling, etc.) may be used and should be documented as part of the process specification.

5.7 AMF preferred (with conversion instructions/ resolutions)

The AMF file format as defined by ISO/ASTM 52915 is the preferred model format for test artifact geometry representation due to its ability to store high fidelity geometry with embedded units in an intermediate file format.

5.8 Need for test specification and test process

This document forms the basis for the general *Test Plan/Specification* described in ASTM F2971:2013, Annex A1, element "D", but specifics about its implementation need recording to accurately document the *Test Process* (element "E" in Annex A1), used for producing the parts as discussed in Clause 6.

5.9 Quantity of test artifacts

For a complete test of machine performance, two things dictate the quantity of the test artifacts produced. First, the Test Specification/Test Process shall ensure a quantity of samples, typically no less than five, so that statistically significant measurements can be made. Second, sufficient coverage (see 5.5) of the build platform needs to be made to account for variations in performance between build locations. Fewer test artifacts with less complete coverage may be used for spot checks or limited demonstrations, such as the example detailed in Annex A. The number of artifacts shall be agreed upon between the buyer and seller and shall permit to perform at least 5 mesurements.

5.10 Position and orientation of test artifacts

As per ASTM F2971:2013, Annex A1, element "F", it is recommended to report results in combination with the test artifacts' build position and orientations according to the convention set forth in ISO/ASTM 52921.

5.11 Considerations for orientation

Since these test artifacts are intended to reveal the strengths and weaknesses of additive building techniques, there will be failed build geometries. It is worth considering which features are likely to fail and place them in a position that minimizes the risk that this leads to an outright failure of the features/parts/artifacts in the rest of the build. For example, in a powder bed process, it can be advisable to position parts that are more likely to fail at a higher level in the overall build to reduce the risk that failed parts or sections of parts impinge on other components in the build or the AM machine mechanism.

5.12 Labelling

It can be useful to add labels to parts in order to identify respective artifact orientations and positions in the build. Labelling is summarised in 7.4.

5.13 Coverage

It is important that test artifacts be made with sufficient coverage of the build volume to get representative data for where real parts are made. Coverage evaluates variability throughout the build volume. This is best practice for all AM processes and is especially critical for processes that have a "sweet spot" (for example, some galvanometric laser beam steering systems give more repeatable results in the centre of the platform). The artifact distribution should span at least 80 % of the machine's build platform area. If build location effects are known or deemed irrelevant for the particular trial being performed, then a single build location may be selected and used, as agreed between vendor and user.

Long artifacts, which reach across the extents of the build, are necessary to detect corrections that are not linear or are periodic in nature.

5.14 Arrays

Geometry should not be scaled (since this affects the measurement outputs) but may be patterned in an array to give larger coverage areas. See an example in Figure 2.

5.15 Part consolidation

When arrays of parts are needed for better coverage, it can be most practical to build a single combined part instead of trying to build arrays of adjacent individual parts. This can be achieved by consolidating adjacent AMF or STL files prior to slicing and other file preparation steps.

As AM most commonly is a layered process (in z-direction) and often based on pixels (in x/y-direction), the exact position of the part in the build can affect the test significantly. This is especially true of artifacts testing machine resolution. A minor translation of the part can influence rounding off issues influencing whether a specific layer or pixel will build or not. This can be caused during preparation of the slice file and during orienting the slice file in to the working area in the machine. Results should be reported in combination with the test artifacts' build orientations according to the convention set forth in ISO/ASTM 52921.

With certain AM processes (especially with metals), heat build-up from processing large cross sectional areas near the test artifacts can affect their geometrical accuracy. Therefore, it is advised that the manufacturer ensure compliance with specified distances.

5.16 Supports and post processing

Where possible, supports should be avoided or supports which do not impede or affect in any way the intended measurement should be employed. Supporting strategy, including, but not limited to material, geometry, removal technique, etc., shall be fully documented in the process specification.

Data reported from this document shall be in the as-built condition prior to any surface or downstream processing. In the case of unavoidable post-processing undertaken prior to measurement (e.g. removal of necessary support material), details of the process should be reported as part of the process specification. The reporting should include a description of any abrasive media and how it was applied to the surface of the artifacts. In addition, data after additional post-processing treatments (such as sand blasting of metal parts for example) may be obtained but only if clearly noted and presented together with as-built measurements.

6 General principles for measuring artifacts

6.1 General

This clause outlines principles applicable for measuring all of the test artifact geometries in this document. The specific measurements are specified in Clause 7 describing the individual artifact geometries. This document does not prescribe any specific measurement methods; the measurements described below can be accomplished by a variety of techniques and devices (e.g. coordinate measuring machine, optical scanner, dial indicators with calibrated motion devices, surface profilometers, etc.). ISO 17296-3 can be used to improve communication between stakeholders concerning test methods. Reporting requirements are previewed in connection with the measurement steps in this clause but more details about recording and reporting can be found in Annexes B and C.

6.2 Measure parts as built

The test artifact should be allowed to cool to room temperature and then measured directly after it is removed from the system used to build it, before any post-processing is performed. The end user may require that parts be held at a set temperature and humidity prior to measurement. If the parts are built by a powder bed based process, the parts should be completely separated from the surrounding powder before measurement. If the parts are built on a build platform, perform the measurements without removing the part from the platform. (Removal from a build platform can affect the shapes of the artifacts, thereby influencing the results. If measurement is not possible on the platform, this shall be explicitly stated in the report.) If post-processing is desired, report all details of each post-processing step and measure the part before and after each post-processing steps (reporting all measurement results).

6.3 Measurement strategy

It is well known that measurement strategy affects the overall measurement uncertainty; this is true for dimensional measurements and surface measurements alike. Measurement strategy, here, involves the device chosen to perform the measurement along with the number of points selected to represent the feature or surface and the distribution of points along the feature or surface. For roughness measurements, the measurement strategy includes any applied filters (e.g. the cut-off length). Measurement strategy is a complicated subject and is often very specific to the part or feature being measured. As such, there is no general "best practice" for performing these measurements. However, some tips are provided in Annexes B and C. The measurement uncertainty is ultimately the important concept, and, with consideration given to the available measurement devices, using a measurement strategy that minimizes the measurement uncertainty within any given constraints should be the primary focus.

Nominally "flat" surfaces may be very uneven or rough. Multiple points sometimes need to be measured to obtain a mean result.

6.4 Measurement uncertainty

The standard uncertainty of each measurement should be reported along with the measurement. Guidance on determining measurement uncertainty can be found in the following references:

— ASME B89.7.3.2 for uncertainty in dimensional measurements;

— ASME B46.1 for surface texture measurements;

— JCGM 100 and JCGM 101 for measurement uncertainty in general;

— ISO/IEC Guide 98-1 and related documents.

Users should document any calibration and/or quality maintenance system for the measurement processes and equipment used. Measurement device and resolution shall be disclosed in the report.

7 Artifact geometries

7.1 General

Seven types of artifacts are described in the following subclauses. Each artifact is intended to test a different aspect of a system's performance or capability.

7.2 Accuracy

7.2.1 Linear artifact

7.2.1.1 Purpose

This artifact tests the linear positioning accuracy along a specific machine direction. Depending on artifact orientation and machine configuration, errors in the artifact may provide a basis for positioning compensation or diagnosing specific error motions in the system's positioning system.

7.2.1.2 Geometry

Figure 1 depicts the geometry of the linear artifact. The artifact is comprised of prismatic protrusions atop a rectangular solid base. A bounding box for the entire feature is 55 mm × 5 mm × 8 mm. The end protrusions are 2,5 mm × 5 mm × 5 mm. The central protrusions are 5 mm cubes. Spacing of the protrusions increases along the length of the artifact from 5 mm to 7,5 mm, 10 mm, and 12,5 mm.

Dimensions in mm

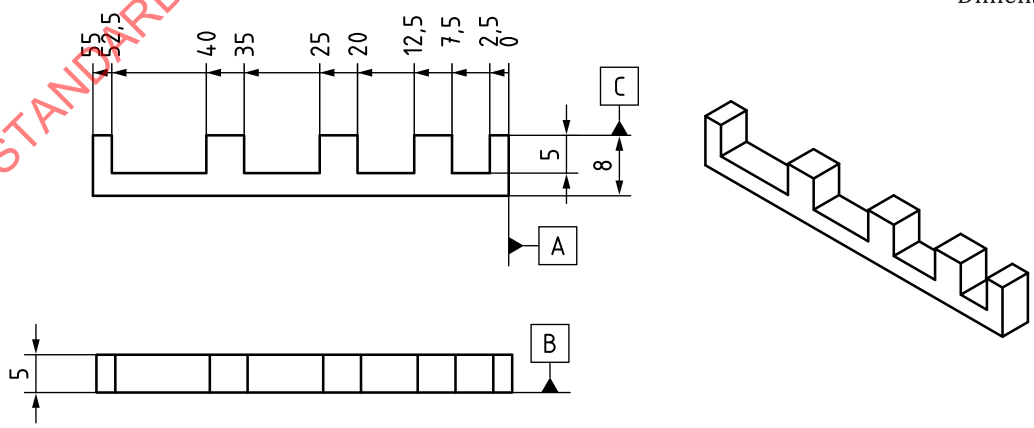


Figure 1 — Engineering drawing of linear test artifacts

If a longer test of linear accuracy is desired, multiple linear artifacts can be appended to one another. The 2,5 mm length of the end protrusions means that when two or more linear artifacts are appended, the central protrusions will all be 5 mm cubes. Figure 2 shows an example. If this option is chosen, see 5.14.

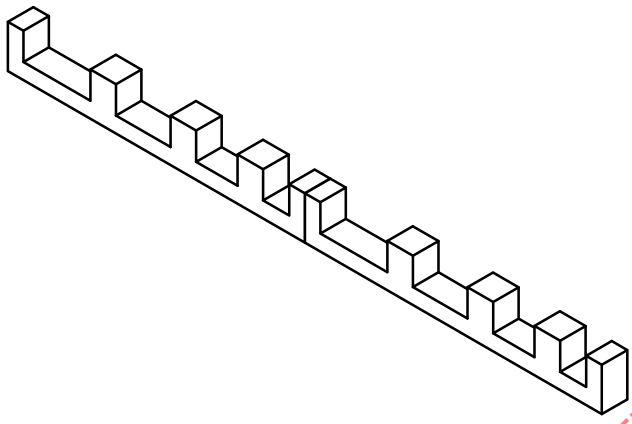


Figure 2 — Two linear accuracy test artifacts appended to each other

If a shorter test of linear accuracy is required, the geometry of an alternative test artifact shall be agreed upon by the user and supplier, and shall follow similar design principles to the part shown in Figure 1. The alternative artifact should have non-equally spaced features and should test both protrusions and gaps (i.e. distances with material in between datum features and distances with space in between datum features).

7.2.1.3 Measurement

The primary measurement for the linear artifact is the positions of the cube faces relative to the primary datum at the end of the artifact (see Figure 1). Alternatively, the lengths of each protrusion can be measured and the spacing between each protrusion can be measured. Optional measurements available are the straightness of the base along the length of the artifact, parallelism of each side of the base along the length of the artifact and the heights of each protrusion.

7.2.1.4 Considerations

Default orientations for a thorough overview of linear accuracy should include at least one test artifact aligned parallel to each axis (x, y, and z) in the machine coordinate system. When this is done, orthogonal orientation notation should be used to document the orientation as per ISO/ASTM 52921. An alternative may be to align one linear artifact with the motion of one of the machine's positioning axes (for example the x-axis slide in a gantry system). This alternative orientation may better link errors in the part with error motions in the positioning system.

Orientations that can cause collision or damage from a wiper or recoating blade should be avoided.

It is often desirable to test linear accuracy through the extent of the machine's positioning capabilities. Users should consider positioning linear artifacts through the middle of the build area as well as near the ends of travel.

In the case of a vertically oriented linear artifact, the use of support structures should be avoided if possible. If support structures are necessary (for example beneath the protrusions), the support strategy (including geometry, material and removal technique) shall be fully documented. Care should be taken to select a support strategy that minimizes the adverse impact on the measuring process/ accuracy.

7.2.2 Circular artifact

7.2.2.1 Purpose

These artifacts are intended to test the dynamic accuracy for the projection of the activation energy (for example a laser-, or an electron beam) or the method of joining material (for example in binder jetting) onto the build surface in the AM machine.

The basic configuration of these artifacts is created to be able to separate the influence of the material and external sources of error that can be present in the AM machine.

7.2.2.2 Geometry

7.2.2.2.1 Basic geometry

Figure 3 depicts the basic geometry of the circular accuracy test artifact. The artifact is comprised of two concentric rings that are closely spaced.

The concentric rings are built centred on a thin circular plate.

The innermost ring is an optional construction.

7.2.2.2.2 Base

The widths of the bases shall have an internal diameter of 20,0 mm for the coarse, 10,0 mm for the medium and 5,0 mm for the fine and an external diameter of 100,0 mm for the coarse, 50,0 mm for the medium and 25,0 mm for the fine. The height of the base shall be respectively 12,0 mm, 6,0 mm and 3,0 mm.

An orientation feature shall be placed at one quadrant of the base cylinder and consist of two flat planes perpendicular to the top plane extending from the centre of the base cylinder, tangential to the external diameter and intersecting outside the cylinder.

7.2.2.2.3 Outer rings

The outer rings have an external diameter of 94,0 mm for the coarse, 47,0 mm for the medium and 23,5 mm for the fine and an internal diameter of 60,0 mm for the coarse, 30,0 mm for the medium and 15,0 mm for the fine. The heights of the rings are respectively 40,0 mm, 20,0 mm and 10,0 mm above the top surface of the base.

7.2.2.2.4 Inner rings

The inner rings have an external diameter of 32,0 mm for the coarse, 16,0 mm for the medium and 8,0 mm for the fine and an internal diameter of 28,0 mm for the coarse, 14,0 mm for the medium and 7,0 mm for the fine. The heights of the rings are respectively 40,0 mm, 20,0 mm, 10 mm above the top surface of the base.

7.2.2.3 Measurement

The primary measurement for this artifact is the roundness (circularity) of the ring faces. Alternatively, the sizes of the diameters of each inner and outer ring can be measured at multiple (minimum five) locations, reporting maximum inscribed circle and minimum circumscribed circle diameters. A second alternative is to measure the wall thickness of each ring at multiple (minimum five) locations. Optional measurements of this artifact include the concentricity of each face of each ring as well as the cylindricity of each face of each ring.

7.2.2.4 Considerations for producing test artifacts

Build position and orientation: multiple rings in build volume should be considered. The artifact should be oriented to allow isolation of two machine motion axes (i.e. reference surface D should be oriented orthogonal to xy, yz, or xz plane).

The use of supports should not be required if the part is built with reference surface D parallel to the xy plane. The base should be a solid structure and substrate to properly anchor the rings to the platform as necessary artifact.

7.2.2.5 Reporting

The reporting on the circular artifact shall contain at least the following information in addition to the measured values:

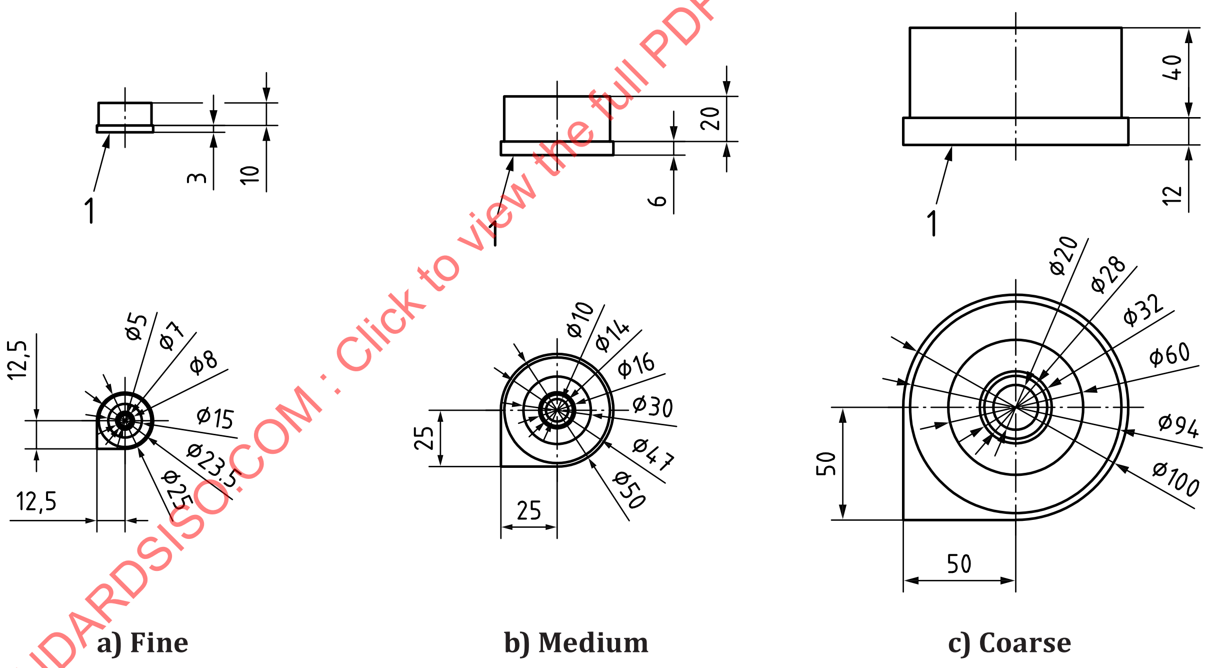
— number of concentric circles;

— nomenclature of the circles as identified on the plate;

— position on plate;

— circle identification (inner to outer).

Dimensions in mm



Key

1 reference surface D

Figure 3 — Engineering drawing of circular artifact

7.3 Resolution

7.3.1 Resolution pins

7.3.1.1 Purpose

This document provides a suite of features intended to assess the ability of the machine/material used to accurately produce fine features at various aspect ratios that are representative of features that can be present in real world parts. The finest pin that can be produced can inform a user about the finest detail that can be produced on the system being examined. The measured diameters of the produced pins give some information about the accuracy of the system.

7.3.1.2 Geometry

Some additive manufacturing processes have a better capability to produce fine features, and the selected resolution pins artifact should provide appropriate sizes to test the system of interest. This document provides three sets of 5-pin features at four different aspect ratios. The 5-pin features have coarse, medium and fine options. The coarse pins range in diameter from 4,0 mm down to 0,5 mm (4,0 mm, 3,0 mm, 2,0 mm, 1,0 mm and 0,5 mm). The medium pins range in diameter from 0,5 mm down to 0,1 mm (0,5 mm, 0,4 mm, 0,3 mm, 0,2 mm and 0,1 mm). The fine pins range in diameter from 0,2 mm down to 0,025 mm (0,2 mm, 0,15 mm, 0,1 mm, 0,05 mm and 0,025 mm). Each of these feature sets is available at 4:1, 6:1, 8:1 and 10:1 length to diameter ratios. Figure 4 depicts the geometry of the medium pins at 6:1.

Dimensions in mm

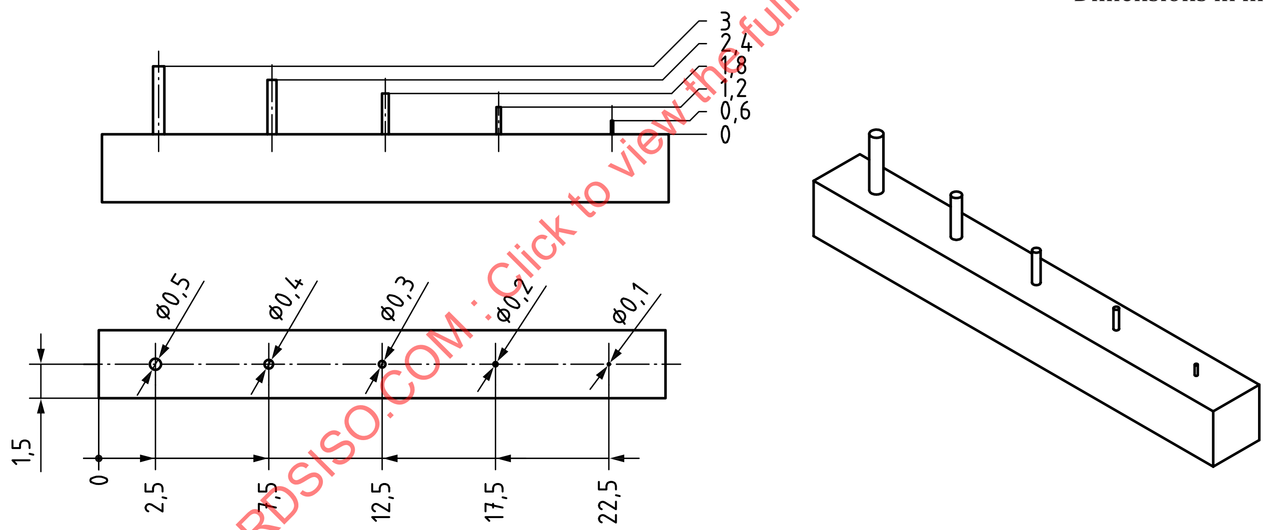


Figure 4 — Engineering drawing of medium resolution pins feature at 6:1 length to diameter ratio

These features are available in coarse and fine features as well.

7.3.1.3 Measurement

The primary measurement for the resolution pins features is the diameters of the pins. The medium and fine pins are spaced at 5,0 mm in an attempt to allow access by an optical microscope objective or by hand measurement equipment (e.g. micrometers or calipers). Optional measurements for the resolution pins are the heights of the pins as well as the cylindricity or runout of each pin.

7.3.1.4 Considerations

It is not intended for the user to build all resolution features available. The user should have an estimated resolution achievable by the system being examined and select the one feature set that spans that estimated resolution. Further, the user may elect to not build that feature set at all aspect ratios. However, it should be noted that in certain systems (e.g. metal PBF systems), the minimum diameter attainable can be different at different aspect ratios.

If the estimated resolution achievable by the system is greater than the largest resolution pin feature set, other standard artifacts can be used to estimate the minimum feature attainable (e.g. the 2,5 mm and 5,0 mm protrusions on the linear artifact).

The minimum pin that can be produced can depend on the build direction, especially when anisotropic processes are examined (e.g. certain AM technologies can provide better resolution in xy-direction than in the z-direction). As such, this test artifact should be built in different orientations in the AM process, for example with the pins parallel to the machine z-direction and with the pins parallel to the machine x-direction. It is recommended that users note any specific reasons for selecting specific orientations (for example if an orientation is selected as a particular challenge to the system or as a best-case scenario).

If selected properly, some pins in the feature will be built successfully by the system while others will fail. Potential pin failure should be considered when positioning the sample within the build volume to avoid adversely affecting the build process for the remaining pins.

If measurement of such fine features is not readily available, the user should note which pins are present, which pins are absent and which pins are deformed or partially formed on the completed build. This observation still provides information on the resolution of the system. If all pins are present, but several appear to be of the same diameter, the pins that are similar in diameter should be noted.

The positions of the pins on the feature can allow measurement of diameter in only one direction when using hand-measuring equipment. If this is the only measurement option available, the user may consider making z-direction pins in two different orientations: with the pins parallel to the machine z-direction and the base aligned to the machine x-direction (zx), and with the pins parallel to the machine z-direction and the base aligned to the machine y-direction (zy).

7.3.2 Resolution holes

7.3.2.1 Purpose

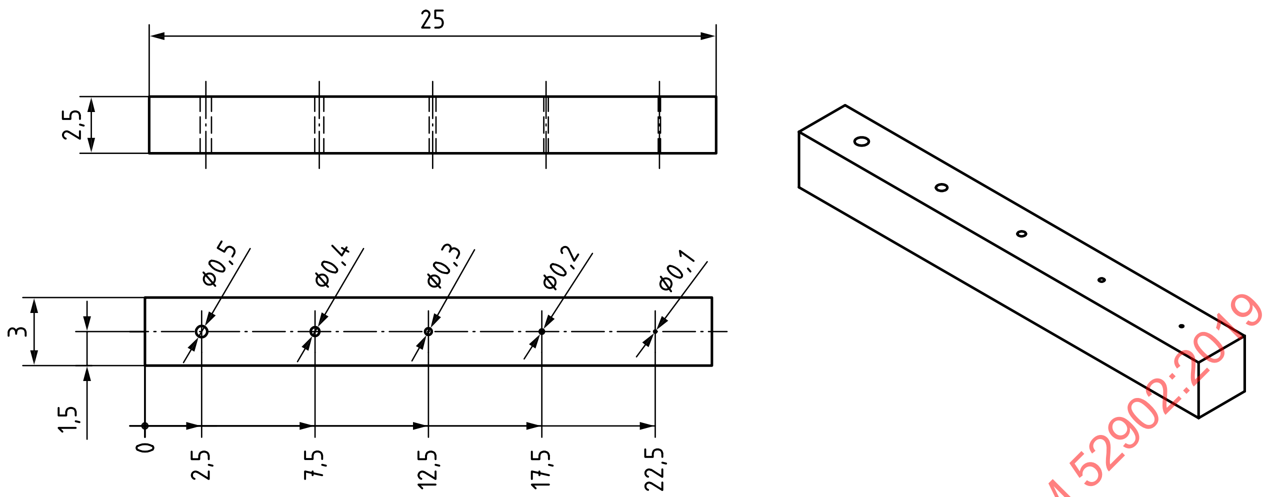
This document provides a suite of features intended to assess the minimum cylindrical feature size attainable at various aspect ratios. The smallest diameter hole that can be produced can inform a user about the finest detail that can be produced on the system being examined. The measured diameters of the produced holes give some information about the accuracy of the system.

In addition to assessing the ability to form the holes, this features also provides a useful indication of the ability to remove unsolidified material from within small holes.

7.3.2.2 Geometry

Some additive manufacturing processes have better capability to produce fine features than others and the selected test feature should provide appropriate sizes to test the system of interest. This document provides three sets of 5-hole features. The 5-hole features have coarse, medium and fine options. The coarse holes range in diameter from 4,0 mm down to 0,5 mm (4,0 mm, 3,0 mm, 2,0 mm, 1,0 mm and 0,5 mm). The medium holes range in diameter from 0,5 mm down to 0,1 mm (0,5 mm, 0,4 mm, 0,3 mm, 0,2 mm and 0,1 mm). The fine holes range in diameter from 0,2 mm down to 0,025 mm (0,2 mm, 0,15 mm, 0,1 mm, 0,05 mm and 0,025 mm). Height of the part is 2,5 mm and the holes are through holes. Figure 5 depicts the geometry of the medium holes.

Dimensions in mm



NOTE These features are available in coarse and fine features as well.

Figure 5 — Engineering drawing of medium resolution holes feature

7.3.2.3 Measurement

The primary measurement for the resolution hole features is the diameters of the holes. The holes are spaced at 5,0 mm in an attempt to allow access by an optical microscope objective or by hand measurement equipment (e.g. pin gauges). Optional measurements for the resolution holes are the depths, roundness (circularity) and cylindricity of the holes.

7.3.2.4 Considerations

It is not intended for the user to build all minimum feature sizes available. The user should have an estimated resolution achievable by the system being examined and select the one feature set that spans that estimated resolution.

If blind holes rather than through holes are desired, the user can easily modify the geometry file to include a solid flat plate beneath the artifact geometry. If this option is chosen, see 5.14. For powder bed based processes, powder removal from small holes can be a significant challenge.

The minimum hole that can be produced can depend on the build direction, especially when anisotropic processes are examined. As such, this test artifact should be built in different orientations in the AM process, for example with the holes parallel to the machine z-direction and with the holes parallel to the machine x-direction. Non-orthogonal orientations are also permissible, and users should consider the impact of stair stepping and layer thickness on hole formation.

If selected properly, some holes in the feature will be built successfully by the system while others will fail. Failed holes will likely still have some surface geometry but will be solid (i.e. filled) below the surface. As such, care shall be taken to examine the feature beyond surface inspection (e.g. by probing with a gauge pin or by other non-destructive evaluation techniques).

If measurement of such fine features is not readily available, the user should note which holes appear properly built, which holes are absent and which holes appear filled on the completed build. This observation still provides information on the resolution of the system. If all holes are present, but several appear to be of the same diameter, the holes that are similar in diameter should be noted.

The holes may be checked with gauge pins for a “go/no-go” assessment (i.e. a pin of certain diameter may fit into the hole — go — while another pin of slightly larger diameter may not fit into the hole — no-go). If this measurement method is chosen, specific guidance in Annex C is strongly recommended. The benefit of this method is that the presence of unwanted material within the hole can be assessed as well as the approximate depth of the hole. The drawback of this method is that it only gives a range of diameters (between the "go" and "no-go" diameters), not an actual hole diameter with known measurement uncertainty. Further, it is likely that the holes are not perfectly round, and therefore this measurement only gives the maximum inscribed diameter. If the entire depth of the hole is not realized, the user should measure and report the depth of the hole (if possible). The primary feature sets match common metric pin gauge sets. Alternative feature sets matching English pin gauge sets are also available. An AM system's capabilities may exceed the limitations of pin gauges (i.e. the smallest hole achievable may be smaller than the smallest gauge pin available).

7.3.3 Resolution rib

7.3.3.1 Purpose

This document provides a suite of features intended to assess the minimum wall thickness attainable by the AM system. The thinnest rib that can be produced can inform a user about the finest detail that can be produced on the system being examined, especially regarding thin walled structures. The measured thickness of the produced rib gives some information about the accuracy and resolution of the system.

7.3.3.2 Geometry

Some additive manufacturing processes have better capability to produce fine features, and the selected test feature should provide appropriate sizes to test the system of interest. This document provides three sets of 6-rib features. The 6-rib features have coarse, medium and fine options. The coarse ribs have wall thickness from 6,0 mm down to 1,0 mm (6,0 mm, 5,0 mm, 4,0 mm, 3,0 mm, 2,0 mm and 1,0 mm). The medium width of the ribs is from 1 mm down to 0,1 mm (1,0 mm, 0,8 mm, 0,6 mm, 0,4 mm, 0,2 mm and 0,1 mm). The fine width of the slots is from 0,1 mm down to 0,01 mm (0,1 mm, 0,08 mm, 0,06 mm, 0,04 mm, 0,02 and 0,01 mm). These features are available at two different wall heights, 10,0 mm tall walls and 20,0 mm tall walls.

Dimensions in mm

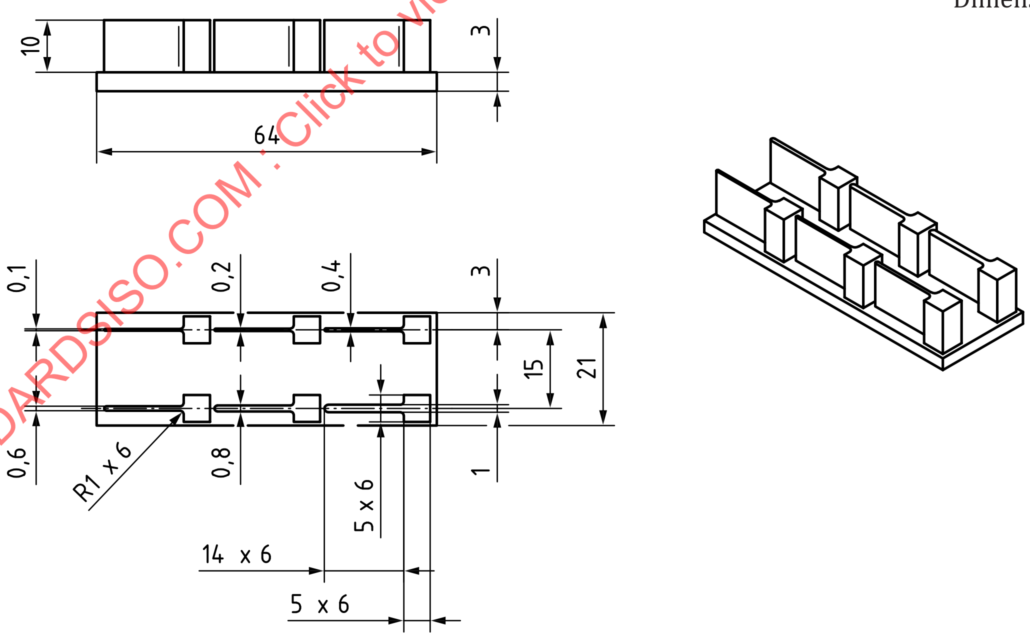
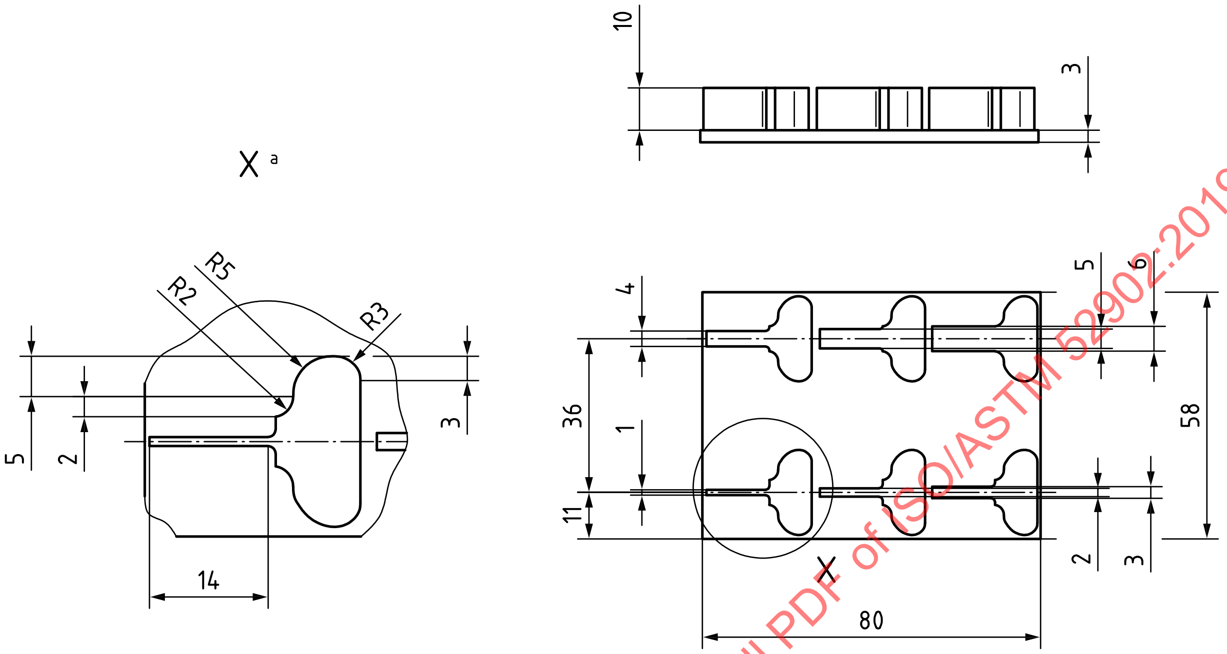


Figure 6 — Engineering drawing of medium resolution ribs feature

These features are available in coarse and fine features, at 10,0 mm and 20,0 mm wall height as well.

Each rib on each feature is supported along one side of the vertical surface by a larger pillar (see Figure 6). This pillar is intended to help identify the location of a rib that may not build properly and to help prevent damage to the rib by any recoating process. The supporting pillar on the coarse radius rib feature has a different geometry (see Figure 7). The geometry in the plane parallel with the base is comprised of three connecting radii or arcs. This allows a user to test the ability of the AM system to meet a profile tolerance.

Dimensions in mm



a Detail A Scale 2 : 1 profile repeated x6.

Figure 7 — Engineering drawing of coarse radius resolution ribs feature

A user can use this feature to measure deviation from a profile.

7.3.3.3 Measurement

The primary measurement for the resolution ribs features is the thickness (width) of the rib. The thickness of the rib should be measured at several locations along the length and height. Methods of measurement include, but are not limited to, handheld calipers or micrometers, calibrated optical microscope and CMM (coordinate measuring machine).

Optional measurements available on this artifact are the length and height of each rib, along with the straightness (both laterally and vertically) of each face of the ribs. Additionally, a profile measurement of the support pillar on the coarse features is available.

7.3.3.4 Considerations

It is not intended for the user to build all resolution features available. The user should have an estimated resolution achievable by the system being examined and select the one feature set that spans that estimated resolution.

If the test artifact is too large to fit within a machine's build volume, the artifact may be modified by the user, subject to agreement between buyer and vendor, to build fewer ribs on one base.

The minimum rib that can be produced can depend on the build direction, especially when anisotropic processes are examined. As such, this test artifact should be built in different orientations in the AM process, for example with the length of the ribs parallel to the machine x-direction and with the ribs parallel to the machine y-direction. It is not intended that the artifact be built with the length of the ribs parallel to the z-direction due to limitations of some processes to building unsupported thin walls.

The orientation of this artifact relative to the direction of motion of any wiper or recoating system should be considered, as bending or breaking of ribs oriented perpendicular to the wiping or recoating direction can be more likely.

If selected properly, some ribs in the feature will be built successfully by the system while others will fail. This failure should be considered when positioning the sample within the build volume.

If measurement of such fine features is not readily available, the user should note which ribs are present, which ribs are absent and which ribs are partially formed or damaged (length and height values on partially formed or damaged ribs can be helpful). This observation still provides information on the resolution of the system. If all ribs are present, but several appear to be of the same width, the ribs that are similar in width should be noted.

The six pillars on each feature are available to test the consistency of the profile creation.

7.3.4 Resolution slot

7.3.4.1 Purpose

This document provides a suite of features intended to assess the minimum slot feature size or the minimum spacing between features attainable. The finest slot that can be produced can inform a user about the finest detail that can be produced on the system being examined. The measured thickness of the produced slot gives some information about the accuracy of the system.

7.3.4.2 Geometry

Some additive manufacturing processes have better capability to produce fine features, and the selected test feature should provide appropriate sizes to test the system of interest. This document provides three sets of 6-slots features. The 6-slots features have coarse, medium and fine options. The coarse width of the slot is from 6,0 mm down to 1,0 mm (6,0 mm, 5,0 mm, 4,0 mm, 3,0 mm, 2,0 mm and 1,0 mm). The medium width of the slots, shown in Figure 8, is from 1,0 mm down to 0,1 mm (1,0 mm, 0,8 mm, 0,6 mm, 0,4 mm, 0,2 mm and 0,1 mm). The fine width of the slots is from 0,1 mm down to 0,01 mm (0,1 mm, 0,08 mm, 0,06 mm, 0,04 mm, 0,02 and 0,01 mm). Each of these features is also available at 5,0 mm wall heights and in coarse features at 20,0 mm and 10,0 mm wall heights and fine features at 5,0 mm and 10,0 mm wall heights. for the medium and fine artifacts. The spacing between two slots is constant: 5,0 mm for the coarse artifact, 2,0 mm for the medium artifact and 1,0 mm for the fine artifact.

Dimensions in mm

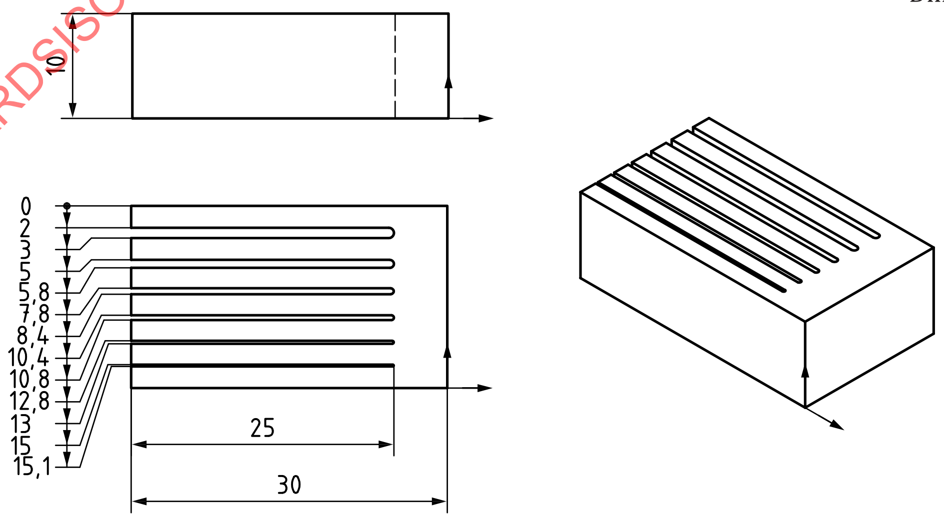


Figure 8 — Engineering drawing of medium resolution slots feature with 10,0 mm high walls

These features are available in coarse and fine features at 5,0 mm and 10,0 mm wall heights as well.

The slots are defined by the space between two arms to protrude from a solid structure connecting all of the arms. The top surface of this connector is parallel to the base of the feature.

On the resolution slotted angle features, the arms each have a different inclination relative to the top surface of the connector (see Figure 9). This allows a user to test the ability of the AM system to meet an angularity tolerance.

Dimensions in mm

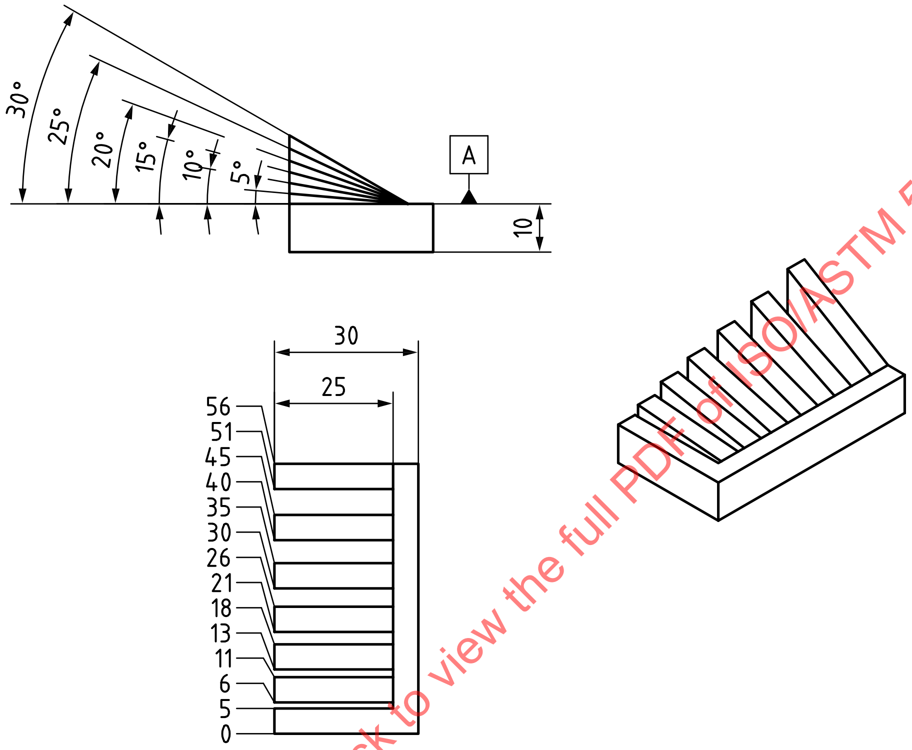


Figure 9 — Engineering drawing of the coarse resolution slots angle feature

The arms are each at a different inclination, allowing a user to check for deviation in angularity.

7.3.4.3 Measurement

The measurement for the resolution slots features is the width of the slot. The slots are spaced at 2 mm in an attempt to allow the user to easily find the intended position of each slot in the case that one or several slots are not successfully built. The width of the slot should be measured at several locations along the slot length. Methods of measurement include, but are not limited to, calibrated optical microscope and feeler gauges.

Optional measurements available on this artifact are the length of each slot, the straightness along the length of each face making up the slots and the parallelism of each face making up the slot.

Additionally, a user can measure the angle formed between the top surface of the connecting structure (labelled A in Figure 9) and the inclined surface of the arm.

7.3.4.4 Considerations

It is not intended for the user to build all resolution features available. The user should have an estimated resolution achievable by the system being examined and select the one feature set that spans that estimated resolution.

If the estimated resolution achievable by the system is greater than the largest resolution slot feature set, other standard artifacts can be used to estimate the minimum feature attainable (e.g. the space between the 2,5 mm and 5,0 mm protrusions on the linear artifact).

The minimum slot that can be produced can depend on the build direction, especially when anisotropic processes are examined. As such, this test artifact should be built in different orientations in the AM process, for example with the slots oriented in the xz plane and the length of the slots parallel to the x-direction or with the slots oriented in the yz plane and the length of the slots parallel to the y-direction.

If selected properly, some slots in the feature will be built successfully by the system while others will fail. This failure should be considered when positioning the sample within the build volume.

If measurement of such fine features is not readily available, the user should note which slots are present, which slots are absent or appear filled on the completed build (length and height values on partially formed or damaged ribs can be helpful). This observation still provides information on the resolution of the system. If all slots are present, but several appear to be of the same width, the slots that are similar in width should be noted.

The build direction of the slots on the feature allows measurement of width in only one direction. As such, the user may consider making z-direction slots in two different orientations: with the slots parallel to the machine z-direction and the base aligned to the machine x-direction (zx), and with the slots parallel to the machine z-direction and the base aligned to the machine y-direction (zy).

7.4 Surface texture

7.4.1 Purpose

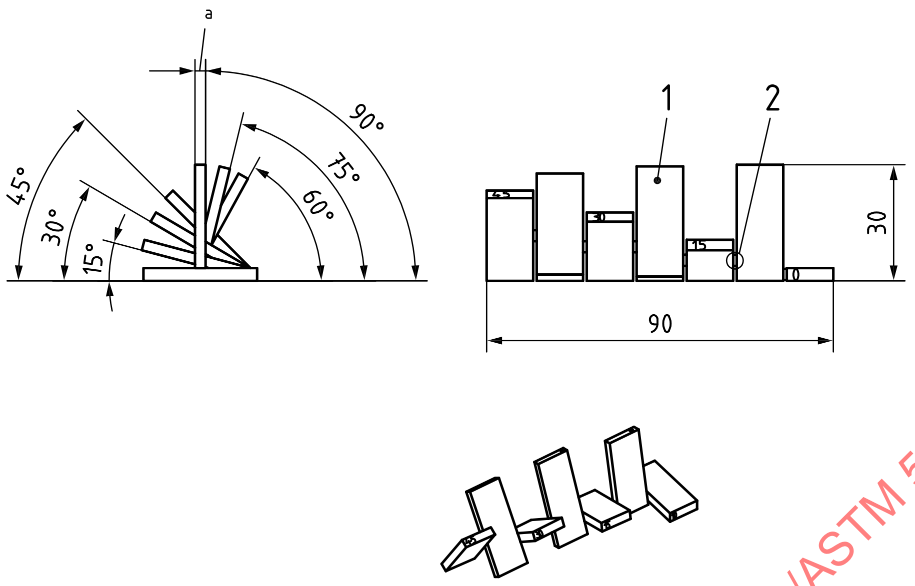
These artifacts test the texture of surfaces produced by an AM system. They enable measurements to be taken using a one-dimensional (profile) measurement method and a two-dimensional (areal) measurement method.

The layered nature of the manufacturing process can leave a stepped geometry on the surface of components. However, in addition to the stepped geometry, several other contributing factors to the surface texture have been found, such as powder particle size (when the feedstock is a powder), extruded diameter (when using material extrusion processes), gravity, heat dissipation, focus spot size (when an energy beam is used) and machine process parameters. These factors cause the surface texture of components made by additive manufacturing to vary over the surface of the component, depending on the local slope of the surface relative to the build direction of the layers. For this reason, the surface texture artifact includes multiple surfaces with different local slope values.

7.4.2 Geometry

Figure 10 depicts the geometry of the surface texture test artifacts. These artifacts are comprised of flat tabs joined with struts. The multiple protruding surfaces allow the surface texture at different surface slopes to be measured. The surface slope angles are 0°, 15°, 30°, 45°, 60°, 75° and 90° with respect to the build platform. The tabs can be measured on both sides. The tabs can be separated by breaking the struts, to allow them to be laid flat and measured. The struts facilitate handling of the artifact during removal from the build chamber. There is no reason why the tabs cannot be built individually, although they can require more supports. Each tab has the surface slope value imprinted on it to help identification once they are separated from each other. The tab dimensions are 6,0 mm × 15,0 mm × 0,4 mm for the fine, 12,0 mm × 30,0 mm × 3,0 mm for the medium and 24,0 mm × 60,0 mm × 6,0 mm for the coarse, which is sufficient for a 5,0 mm × 8,0 mm areal measurement or a 12,5 mm profile measurement on each tab.

Dimensions in mm



Key

1 strip (3 mm × 12 mm × 30 mm)

2 one of the six off connection structs

a Thickness of the strip.

Figure 10 — CAD models of surface texture artifacts

It is recommended that all samples be built, but fewer can be built if agreed upon by buyer and seller.

7.4.3 Measurement

Method: the texture of the surface can be measured by tactile or optical method, taking a profile measurement or an areal measurement. In addition to the actual surface texture measurements, the method used and measurement parameters should be recorded.

If profile measurements are chosen, they should be taken in a direction perpendicular to the lay of the texture, i.e. along the length of each sample. The direction of measurement does not need to be recorded. Profile measurements should be repeated multiple times (at least 3) on each surface, at different locations; see Figure 11. The top surface of the horizontal (90°) artifact can have surface texture effects caused by the scanning and/or hatching strategy used during the process. The top surface measurements can therefore give different results depending on process parameter settings and position in build chamber.

Key

1 tab surface to be measured

a Suggested profile measurement positions.

b Suggested areal measurement position.

Figure 11 — Suggested locations for profile and real measurements

Where possible, both surfaces (upward and downward facing) of each tab of the artifact should be measured and reported separately.

7.4.4 Reporting

The roughness measurement parameters shown in Table 1 should be measured and reported (refer to ASME B46.1 or ISO 4287/ISO 4288/ISO 25178). The profile length should also be reported for profile measurements and the area measured should be reported for areal measurements. Suggested values are given in ASME B46.1 or ISO 4287/ISO 4288/ISO 25178.

Table 1 — Suggested measurement parameters

Name	Symbol (profile measurement)	Symbol (areal measurement)
Average roughness (arithmetical mean deviation) of the surface	R_a	S_a
Average peak to valley height of the surface	R_z	S_z
Skewness (the degree of asymmetry) of the surface height distribution	R_{sk}	S_{sk}
Kurtosis (the degree of peakedness) of the surface height distribution	R_{ku}	S_{ku}

A selection of filters (mechanical, electrical and/or software) is applied when measuring surface texture. The filters used should be disclosed with the measurement results. As a minimum, the value of the filters shown in Table 2 should be reported. The value of other software filters that can have been used — for example a phase correcting filter — should be recorded.

Table 2 — Typical values of measurement filters

Measurement type	Filter symbol	Filter Name	Typical values
profile	λ_c	Low-pass filter	Same as sampling length
	λ_s	High-pass filter	Radius of measurement stylus tip
areal	L-filter	Large scale filter	Same as one side of the measurement area
	S-filter	Small scale filter	10 µm

The filters used as well as the profile length or measurement area should be taken into account when comparing surface texture characterisation results obtained from different sources. Appropriate parts of ASME B46.1 shall be followed. Comparisons between measurements are only appropriate when made using identical methods.

7.4.5 Considerations

7.4.5.1 Build orientation

The artifact should be built in the upright position, i.e. with the base parallel to the build platform. If the tabs are built individually, they should be built at the angle from the build platform that is imprinted on the tab, with their short edge parallel to the build platform. Orientations that result in edges parallel to the wiper or recoater blade should be avoided.

7.4.5.2 Repeatability

The surface texture of parts produced by the process can vary with position in the build chamber and with orientation of the artifact with respect to the axes of the machine. Therefore, if comparison with other results is required, the position and orientation of the artifacts in the build chamber should also be recorded.

7.4.5.3 Supports

For AM processes that create support structures built from the same material as the artifact, minimizing the use of these supports where possible enables a greater number of different surface slopes to be measured, especially on downward facing surfaces of the test artifacts. Where such supports are unavoidable, it is sometimes possible to adjust the spacing between them, to allow room for a measurement tool to access the surface to be measured. In addition, for some AM processes, the scan and/or hatch parameters can be adjustable to produce supports that can be removed more easily, minimizing the witness marks and risk of damage to the surface being measured. Users should consult the machine supplier's documentation for further information.

7.4.5.4 Recoater

When AM systems fitted with recoating systems are used, care shall be taken to avoid orientating the parts such that collision between the part and the recoating system would cause the parts to pull up or fold back.

7.5 Labelling

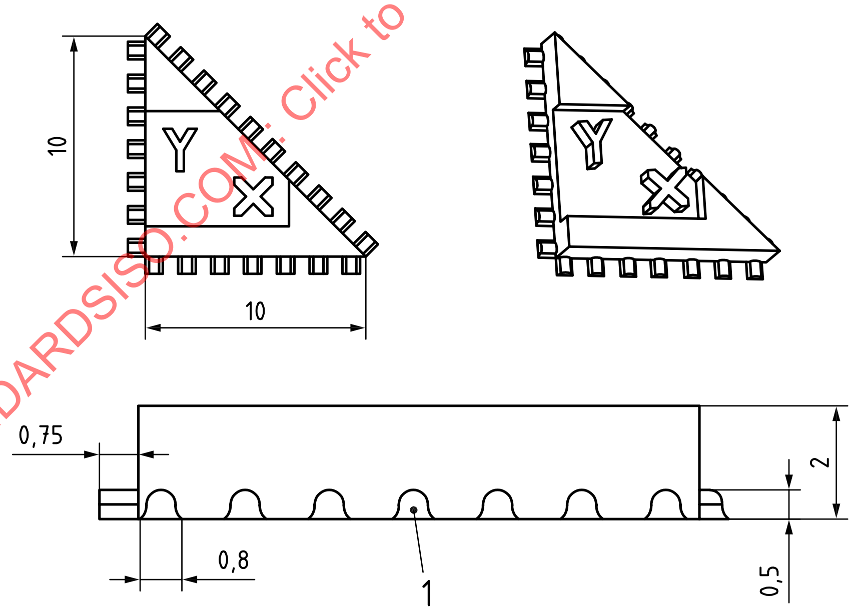
7.5.1 Purpose

Labels can optionally be included in a build to identify respective artifact orientations and positions. These labels may be included on the build platform or on the parts themselves, as long as they are positioned so that they do not interfere with the properties to be measured.

7.5.2 Geometry

A label indicating the machine x and y build directions is available with the test artifact geometries and is shown in Figure 12. Struts facilitate easy detachment of label from artifact following build.

Dimensions in mm



Key

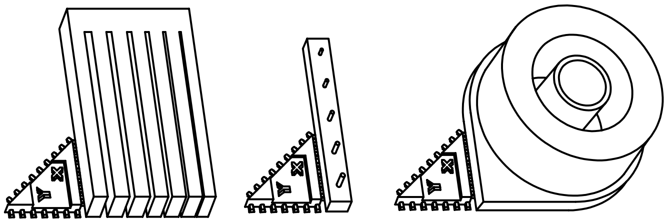
1 Strut A

Figure 12 — Engineering drawing of XY-label

7.5.3 Considerations

When adding labels, it can be advisable to do so with a non-symmetrical feature/shape to help describe artifact position and ensure it cannot be misinterpreted. An example use of label with artifact is shown in Figure 13.

a)



b)

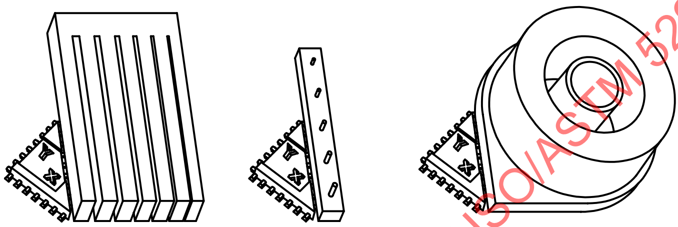


Figure 13 — XY label attached to build at a) 0°, 90° and b) 45°

Annex A
(informative)

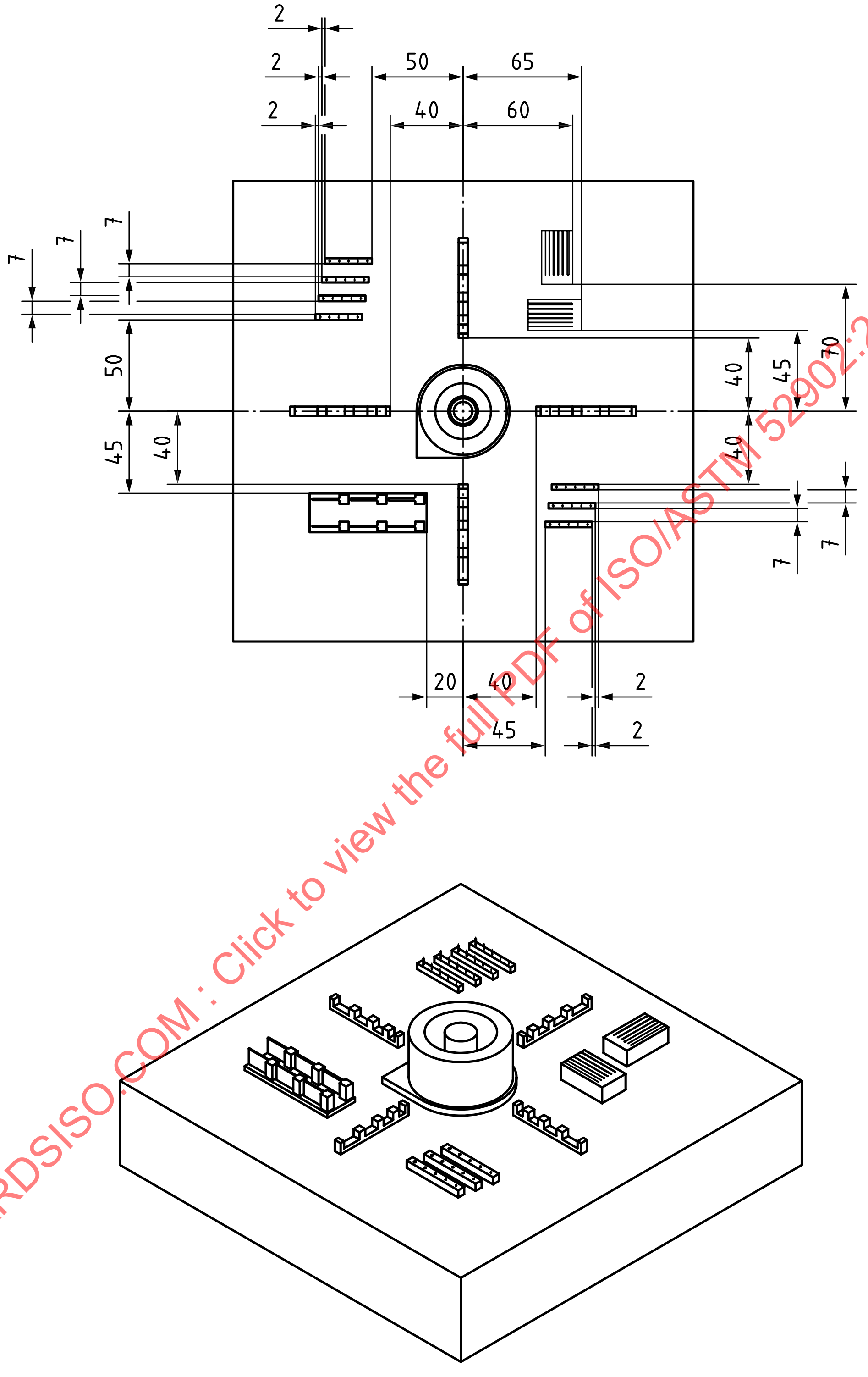
Example artifact configurations

Users are encouraged to configure the artifacts described in the main text of this document with positions and orientations that best address their specific needs. However, in cases of general inquiry, it can be helpful to have a generic configuration. This annex provides several example artifact configurations that can easily be adopted by a user.

The required and optional measurements discussed in the main body of this document all pertain to the individual artifacts. However, there is no language precluding the measurements of positions and orientations of the artifacts relative to each other. Several of the configurations below take advantage of these relative position and orientation errors to provide additional measures of system geometric performance.

A quick check of x/y performance can be performed. This configuration is intended to provide data on the geometric performance of the system in the xy plane, especially toward the centre of the build platform. Further, this configuration is intended to build quickly and require a small amount of feedstock material. The small number of test artifacts and the shallow build height mean that this is not a thorough characterization of system performance.

Dimensions in mm



NOTE 1 Artifacts used:

— linear artifact (x4);

— circular artifacts (x1);

— resolution pin artifacts (x4);

— resolution hole artifacts (x3);

— resolution rib artifacts (x1);

— resolution slot artifacts (x2).

NOTE 2 Linear artifacts are aligned to the x-axis or y-axis to highlight error motions of individual machine axes.

NOTE 3 Measurements of perpendicularity between linear artifacts can highlight errors in squareness between machine motion axes.

Figure A.1 — Engineering drawing and CAD model drawing of example build for quick check in xy plane

The circular artifact and the four linear artifacts are symmetric about the centre of the build platform, which can be helpful in highlighting errors in systems where the scanning source is mounted above this centre point.

Annex B
(informative)

Measurement techniques

B.1 General

While this document does not prescribe specific measurement methods, there are common methods that are anticipated to be helpful in measuring the various measurands on each artifact. These measurement methods and their associated equipment vary in difficulty, uncertainty, and cost. Accordingly, the measurement methods are divided into three categories:

— grade A for simple and inexpensive measurements commonly available in a shop;

— grade AA for slightly more difficult methods;

— grade AAA for laboratory level measurements that are expensive and involved but result in the lowest measurement uncertainty.

The different measurement methods for several measures and (many of which are optional) measurements on each artifact are summarized in Table B.1 below.

The expected deviation of the measurand from nominal should be taken into consideration when selecting an appropriate measurement method. Specifically, many users can require that the measurement uncertainty be at least four times better than the value being measured (though ten times is sometimes preferred). For example, if the roundness (circularity) deviation of the inner ring of the circular artifact is expected to be 0,5 mm or better, the selected measurement method should be able to achieve a roundness measurement uncertainty no larger than 0,125 mm (though 0,05 mm may be preferred). This is known as the test to uncertainty ratio (TUR), and more information can be found in ISO/IEC 17025/ ANSI NCSL Z 540.3.

Table B.1 — Suggested measurement methods and main characteristics of test artifacts

Measurand	Output	Measurement method	Measurement grade
Linear artifact			
Position	Coordinate of each face	CMM	AAA
	Coordinate of each face	3D scanner	A to AA
	Protrusion thickness	Handheld micrometers or calipers	A
	Spacing between protrusions	Handheld calipers	A
Straightness	Form along the length of artifact	CMM	AAA
	Form along the length of artifact	3D scanner	A to AA
	Form along the length of artifact	Dial indicator with calibrated positioning stage	AA
	Form along the length of artifact	Dial indicator with straight-edge	A
Circular accuracy artifact			
Roundness (circularity)	Form of the individual faces of each ring	CMM	AAA
	Form of the individual faces of each ring	Roundness measuring device	AAA

Table B.1 *(continued)*

Measurand	Output	Measurement method	Measurement grade
	Form of the individual faces of each ring	Dial indicator and calibrated rotary axis	AA
	Diameter at several points (difference between maximum inscribed and minimum circumscribed circles)	Handheld calipers or micrometers	A
Diameter	Diameter of best-fit circle to multiple points	CMM	AAA
	2-point diameter	Handheld calipers or micrometers	A
Concentricity	Centre positions of best-fit circles to faces of each ring	CMM	AAA
	Form deviation of one face of ring relative to reference location	Dial indicator and calibrated rotary stage	AA
Resolution pins			
Pin diameter	Minimum circumscribed circle	CMM	AAA
	Minimum circumscribed circle	Calibrated microscope	AA to AAA
	Maximum inscribed circle	3D scanner	A to AA
	2-point diameter	Handheld micrometers or calipers	A
Pin height	N/A	CMM	AAA
		Depth gage or handheld caliper	A
Roundness (circularity)		Calibrated microscope	AA to AAA
		CMM	AAA
Cylindricity		CMM	AAA
		3D scanner	A to AA
Resolution holes			
Diameter	Maximum inscribed circle	Calibrated microscope	AA to AAA
	Best fit circle	Calibrated microscope	AA to AAA
	Maximum inscribed circle	Pin gage	A
Hole depth		Pin gage with depth gage	A
Roundness (circularity)		Calibrated microscope	AA to AAA
Resolution ribs			
Rib thickness		CMM	AAA
		Handheld calipers or micrometers	A
Straightness (or flatness)	Form of artifact	CMM	AAA
	Form of artifact	3D scanner	A to AA
	Form of artifact	Dial indicator with calibrated positioning stage	AA
	Form of artifact	Dial indicator with straightedge	A
Resolution slots			
Slot width	Distance between faces	Feeler gauges (gauge shims)	A
	Distance between faces	CMM (coarse slots only)	AAA

Table B.1 *(continued)*

Measurand	Output	Measurement method	Measurement grade
	Distance between faces	Handheld calipers or micrometers (coarse slots only)	A
Flatness	Deviation from best fit plane	CMM (coarse slots only)	AAA
Parallelism		CMM (coarse slots only)	AAA
Surface texture			
Average roughness	R_a	Contact (stylus) profilometer	AA to AAA
	S_a	Optical profilometer	AA to AAA
Skewness	R_{sk}	Contact (stylus) profilometer	AA to AAA
	S_{sk}	Optical profilometer	AA to AAA
Kurtosis	R_{ku}	Contact (stylus) profilometer	AA to AAA
	S_{ku}	Optical profilometer	AA to AAA
Others to be added			

B.2 Suggestions for dimensional measurement

In general, repeating a measurement several times and taking the average value over those measurements reduces measurement uncertainty. A minimum of three replicate measurements on each measurand is suggested.

Minimal force should be applied to the measured part or feature, especially for small fragile geometries.

The user is encouraged to look for possible non-flat or “turned-up edges” on nominally flat faces that can affect results.

With high roughness surfaces, the measured dimension is systematically larger than the amount of solid material present because measurement probes systematically capture peaks in the surface more than they capture valleys in the surface.

For coordinate measuring:

— More points is always preferred.

— It is recommended that at least 80 % of the surface be covered by the range of the coordinate measurements.

— A stratified random coverage of a surface generally results in a lower measurement uncertainty than a uniform coverage of a surface.

For measurements with an optical microscope:

— Edge detection plays a large role in bias and precision. Careful analysis should be made of the employed edge detection method and its contribution to measurement uncertainty.

— Lighting affects the quality of the image and therefore the edge detection. A repeatable procedure for achieving uniform lighting (while avoiding saturation) with the equipment available helps reduce measurement uncertainty.

Annex C
(informative)

Measurement procedures

C.1 General

The measurement procedures described in this annex are not necessarily preferred over other measurements for the same measurand. For example, when measuring the positions of the faces of the protrusions in the linear artifact, measurements using a CMM result in lower measurement uncertainty than measurement using dial or digital calipers. However, complete description of how to operate a CMM for optimal measurement of position is outside the scope of this annex. Contrarily, the simplicity of using dial or digital calipers allows for more complete discussion of measurement procedures. Further, the simplicity of use often leads users to be less mindful of precision measurement concepts, which are reinforced in the procedures that follow.

C.2 Linear artifact

C.2.1 Equipment for measurement

Digital micrometer screw or digital calipers, with a maximum permissible error (MPE) ≤0,02 mm. A micrometer screw offers a larger contact area than digital calipers. Digital calipers can give inaccurate results if, for example, the jaws are placed parallel to the build direction and make contact between built layers.

C.2.2 Instructions for benchmark measurement

Each distance should be measured three times at varied heights up the cube:

— 1st measurement on bottom surface;

— 2nd measurement mid-way up cube;

— 3rd measurement at top of cube.

C.2.3 Considerations for measuring benchmark

Lip edge as shown in Figure C.1 gives variations in measurements if measurements are taken from the edge. Positions should be kept consistent throughout the measurement procedure and localized features such as this should be avoided whenever possible during measurement.

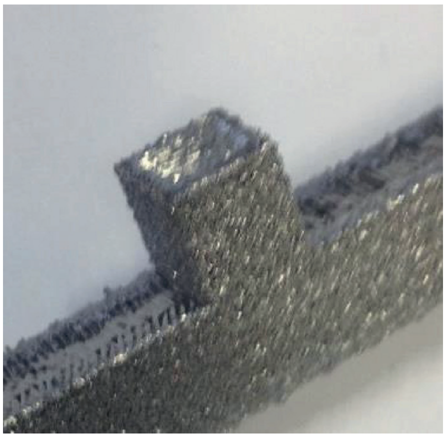


Figure C.1 — Raised edges formed on top surface of geometry

C.3 Circular artifact

C.3.1 Equipment for measurement

— Optical Measurement, CMM, or equivalent.

C.3.2 Instructions for benchmark measurement

— Roundness of the rings:

(Measurement dimensions are shown in Figure C.2. The *E*, *D* and *F* dimensions used depend on the circular artifact chosen for measurement.)

— Scan should start at Pt1.

— Pt1 is 0,5*D* mm from Plane -B- and 0,5(*D*-*E*) mm from Plane -A-.

— The scan should be continuous to end back at Pt1.

— The scan should be performed at a plane parallel to Surface -C- at a height 0,5*F* mm from Surface -C-.

— Concentricity/cylindricity of the rings:

— The circles/cylinder should be measured/constructed at two heights parallel to Surface -C- at heights 0,25*F* mm and 0,75*F* mm from Surface -C-.

— The measurements shall be relative to the axis -G- relative to the external diameter *D*.

— Size:

— The internal and external diameters shall be measured at two heights parallel to Surface -C- and averaged. The measurement should be taken at heights 0,25*F* mm and 0,75*F* mm from Surface -C-.

— Wall thickness of the rings:

— The thickness of the walls shall be measured at five or more locations.

— Pt1 shall coincide with Pt1 used in the roundness measurement.

— The subsequent points should be measured at the following angular locations: Pt2 – 72°, Pt3 – 160°, Pt4 – 216°, and Pt5 – 285°.