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# Additive manufacturing of metals — Finished part properties — Orientation and location dependence of mechanical properties for metal powder bed fusion

*Fabrication additive de métaux — Propriétés des pièces finies — Dépendance de l'orientation et de l'emplacement sur les propriétés mécaniques pour la fusion sur lit de poudre métallique*



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# Contents

Page





# 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 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.

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

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

AM produced metallic parts are being intensively developed and used more widely today with an expected faster growth in near future. This document aims to support customers' needs to address specifics of the AM deposited parts – location and orientation dependent local properties and their variations over the part or deposition chamber.

This document provides a list of accurate terminologies and existing standards dedicated to mechanical testing of metallic materials, guidance on designation of coordinate systems and their application to AM specimens/parts designation, and recommendations on possibilities for local properties measurement.



# Additive manufacturing of metals — Finished part properties — Orientation and location dependence of mechanical properties for metal powder bed fusion

## 1 Scope

This document covers supplementary guidelines for evaluation of mechanical properties including static/quasi-static and dynamic testing of metals made by additive manufacturing (AM) to provide guidance toward reporting when results from testing of as-build specimen or those excised from printed parts made by this technique or both.

This document is provided to leverage already existing standards. Guidelines are provided for mechanical properties measurements and reporting for additively manufactured metallic specimen as well as those excised from parts.

This document does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health and environmental practices and determine the applicability of regulatory limitations prior to use.

This document expands upon the nomenclature of ISO/ASTM 52900 and principles of ISO/ASTM 52921 and extends them specifically to metal additive manufacturing. The application of this document is primarily intended to provide guidance on orientation designations in cases where meaningful orientation/direction for AM cannot be obtained from available test methods.

## 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 1099, *Metallic materials — Fatigue testing — Axial force-controlled method*

ISO 4506, *Hardmetals — Compression test*

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

ISO 12106, *Metallic materials — Fatigue testing — Axial-strain-controlled method*

ISO 12108, *Metallic materials — Fatigue testing — Fatigue crack growth method*

ISO 12135, *Metallic materials — Unified method of test for the determination of quasistatic fracture toughness*

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

ISO/ASTM 52921, *Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies*

ASTM E8/E8M, *Standard test methods for tension testing of metallic materials*

ASTM E9, *Standard test methods of compression testing of metallic materials at room temperature*

ASTM E399, *Standard test method for linear-elastic plane-strain fracture toughness kic of metallic materials*

ASTM E466, *Standard practice for conducting force-controlled constant amplitude axial fatigue tests of metallic materials*

ASTM E561, *Standard test method for k-r curve determination*

ASTM E606/E606M, *Standard test method for strain-controlled fatigue testing*

ASTM E647, *Standard test method for measurement of fatigue crack growth rates*

ASTM E1820, *Standard test method for measurement of fracture toughness*

ASTM E1921, *Test Method for Determination of Reference Temperature, $T_o$, for Ferritic Steels in the Transition Range*

ASTM E2472, *Standard Test Method For Determination Of Resistance To Stable Crack Extension Under Low-Constraint Conditions*

ASTM E2899, *Standard test method for measurement of initiation toughness in surface cracks under tension and bending*

ASTM F2971, *Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing*

## 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 https://www.electropedia.org/

### 3.1 Definition

**3.1.1**
**part location**
location of the part/sample/specimen within the build volume

Note 1 to entry: The part location is normally specified by the *x*, *y*, *z* coordinates for the position of the geometric centre of the part´s bounding box with respect to the build volume origin.

### 3.2 Abbreviations

The abbreviations used in this document, and in particular in Figure A.1, are listed in Table 1.

**Table 1 — Abbreviations**

| Abbreviation | Signification | Comment |
|---|---|---|
| S | Start | Any base of the specimen or part that provides a surface upon which deposition starts (see Annex A). |
| E | End | Any area of a specimen or part that provides a surface upon which the specimen or part deposition ends (see Annex A). |
| M | Middle | Mid-plane of a specimen or part between start and end (see Annex A). |
| B | Both | Crack growth captures both start and end of build (see Annex A). |
| RD | Scan direction | This may or may not be the same throughout the build (see Annex A). |

### 3.3 Acronyms

The acronyms used in this document for illustrating crack growth directions with respect to the build direction are listed in Table 2 and illustrated in Figure A.4.

**Table 2 — Acronyms**

| Acronym | Signification |
|---|---|
| XY, YX, XZ, ZX, YZ, ZY | The first letter represents the direction normal to the crack plane and the second letter represents the expected direction of crack extension. |
| XYB | Indicates that crack growth captures both the start and end of the build in XY direction. |
| XZE | Indicates that the crack growth occurs from the end to the start of build in the XZ direction. |
| XZS | Indicates that the crack growth occurs from the start to the end of build in the XZ direction. |
| YXB | Indicates that crack growth captures both the start and end of the build in YX direction. |
| YZE | Indicates that the crack growth occurs from the end to the start of build in the YZ direction. |
| YZS | Indicates that the crack growth occurs from the start to the end of build in the YZ direction. |
| ZXM (or ZX1/2) | Indicates that crack growth occurs at the middle plane in ZX direction. |

In situations in which a test specimen is created from other locations with respect to the start of the build (for example ¼, ¾, etc. distance from the start of the build) in the ZX direction, the notation used should indicate this location. For example, ZX1/4 indicates that testing was conducted in the ZX direction at a location one quarter of the way from the start of the build.

In situations where a test specimen (i.e. either a standard size or miniaturized specimen) is excised from a portion of the build volume (e.g. from an actual part) this should be noted. The terminology provided above should still be used to indicate the location of the excised sample with respect to the original build volume.

## 4 Summary of document

**4.1** The purpose of this document is to provide guidelines for test methods referenced in Clause 2 and also use some of the terminologies defined in ISO/ASTM 52900 with metal additive manufacturing test specimens. Test specimens may be built directly to net-shape, or near net-shape, or excised from a part.

**4.2** Standard geometries can be used based on the reference standards indicated in Clause 2, however, direct testing of a part is a highly recommended practice for metal AM (See A.6).

**4.3** In order to investigate and document orientation and location-specific mechanical properties, cut small-scale specimen from the relevant locations of the parts should be achieved. This document describes some principles to apply for the testing of various properties.

## 5 Significance and use

**5.1** Although evaluation of mechanical properties of many additively manufactured materials can be conducted using the guidelines developed for conventional materials within existing testing standards, the coordinate systems and nomenclature specific to conventional materials testing (for example in ASTM E399, ASTM E647, ISO 12108 and ISO 12135) are not sufficient to be applicable across the full spectrum of specimens/parts produced by metal AM without causing confusion. This document is based on the nomenclature and principles of ISO/ASTM 52921 and extends them specifically to metal AM. The application of this document is primarily intended to provide guidance on orientation designations in cases in which meaningful orientation/direction for AM cannot be obtained from available test methods.

**5.2** It shall be understood that the interpretations and guidelines in this document do not alter the validity requirements of test methods nor can this document be used to change the designation of “invalid” data (that is according to test methods) to a “valid” condition. This document is primarily concerned with cases in which it is not possible or practical to obtain meaningful data based on orientation/direction designations that are currently covered in standards developed for conventionally processed materials.

## 6 Procedure

The test procedure, analysis of test record, and calculations shall be made in accordance with Table 3.

**Table 3 — Standards to be applied according to test method**

| Test method | Referenced standards |
|---|---|
| tensile | ASTM E8/E8M, ISO 6892-1 |
| compression | ASTM E9, ISO 4506 |
| force controlled fatigue | ASTM E466, ISO 1099 |
| strain-controlled fatigue | ASTM E606/606M, ISO 12106 |
| linear elastic fracture toughness | ASTM E399 |
| $K_R$ curve determination | ASTM E561 |
| non-linear fracture toughness | ASTM E1820, ASTM E1921, ASTM E2472, ASTM E2899, ISO 12135 |
| fatigue crack growth | ASTM E647, ISO 12108 |

## 7 Report

### 7.1 General

The report shall include all the information required by test methods along with the location and orientation of the part or specimen, following the guidance provided in this document.

### 7.2 Additional requirements

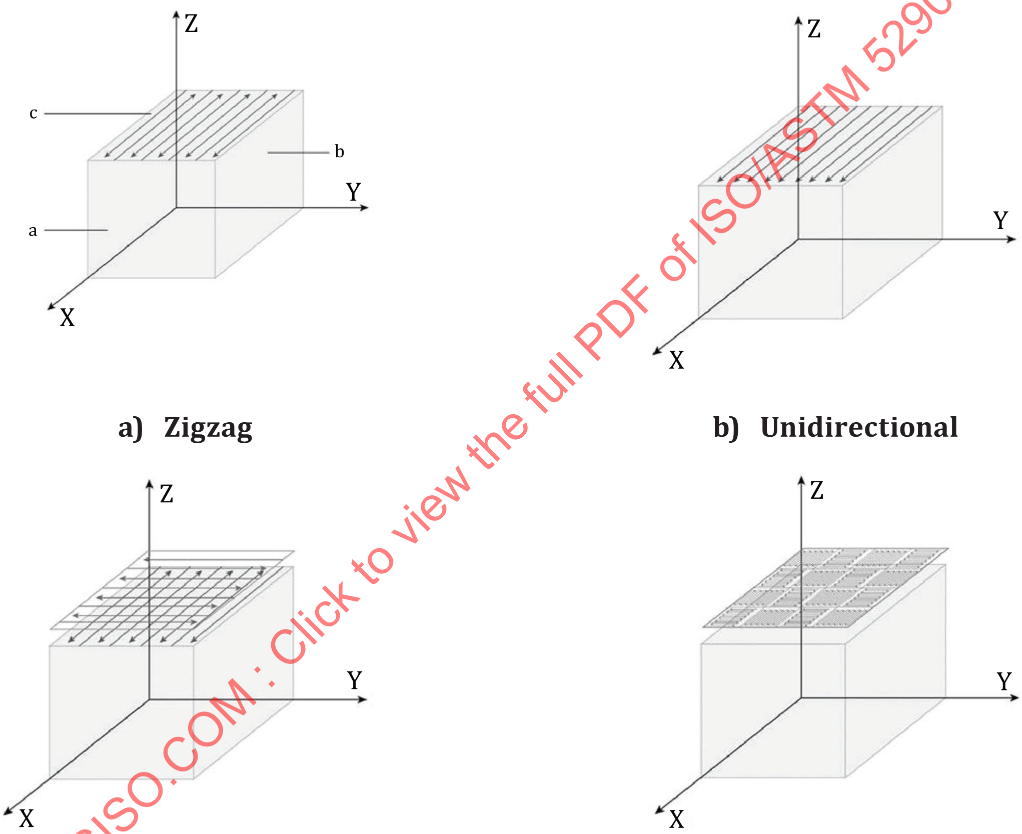
Since the scan strategy can have a significant effect on the mechanical properties of the parts, it is highly recommended that a specification of the scan strategy is included in the test report for metallic materials. There are a number of different strategies that can be used to manufacture a part. Some of the common scan strategies are included in A.1. However, different types of scan strategies can be used depending on the type of AM machine used. Besides the scanning strategy, other process parameters that can have significant influence on the mechanical properties in the parts include, but are not limited to: preheating of the base plate, scanning speed, spot size, scan path overlaps and others. Because of variation in scan strategies typically used in AM, it is not possible to relate the orientation nomenclatures to the scan strategy directly. Conventional directions typically used for deformation processing have been used presently to define the axes and terminologies. Processing/post-processing parameters shall be reported in accordance with ASTM F2971.

# Annex A
(informative)

# Example raster (scan) strategies for reporting

## A.1 Example of strategies for reporting

All units are expressed in SI system. Figure A.1 gives example of strategies for reporting.




a) Zigzag

b) Unidirectional

c) Cross hatching

d) Island

**Key**

X scanning direction
Y Y axis
Z build direction
a Front.
b Side.
c Top.

**Figure A.1 — Example raster (scan) strategies for reporting**

## A.2 Rectangular specimens orientations designation for tensile, low- and high-cycle fatigue testing

The orientation of the specimen in the build chamber shall be identified by orthogonal orientation notation as specified in ISO/ASTM 52921. This nomenclature can be used for tests on rectangular specimens in which there is no starter crack/notch requirement. These test methods are not limited to ASTM E8/E8M and ISO 6892-1 (tensile), ASTM E9 and ISO 4506 (compression), ASTM E466 and ISO 1099 (force-controlled fatigue), and ASTM E606/606M and ISO 12106 (strain-controlled fatigue). For test methods that require a starter crack/notch, see A.4.

Figure A.2 illustrates possible orientation designation for tensile, low and high-cycle fatigue testing for rectangular specimens.

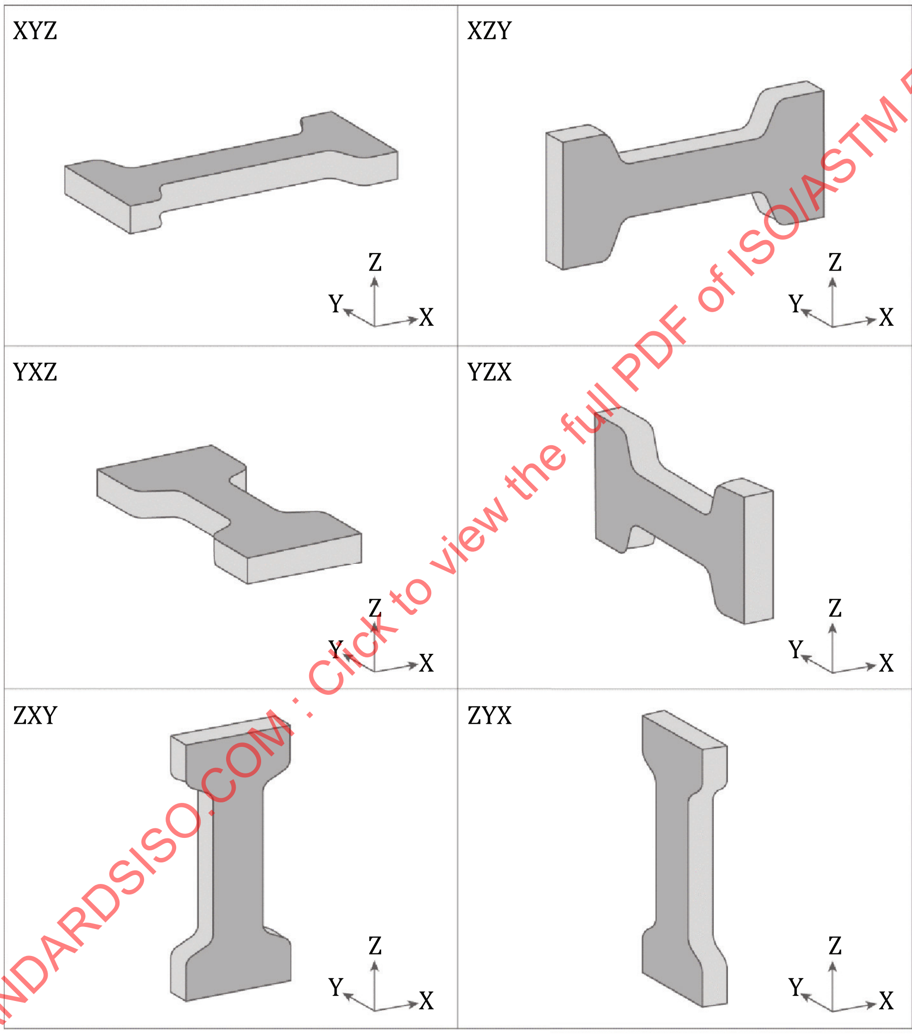





**Figure A.2 — Specimen orientations illustrating example orientation designation for tensile, low and high-cycle fatigue testing for rectangular specimens**

NOTE Orientations shown in Figure A.2 are based on ISO/ASTM 52921. For example, for the XYZ specimen, the longest dimension is parallel to the X axis, the second longest dimension is parallel to the Y axis and the shortest dimension is parallel to the Z axis. The Z axis is always the build direction.

## A.3 Round specimen orientations for tensile, low-, and high-cycle fatigue testing

Figure A.3 illustrates possible orientation designation for tensile, low and high-cycle fatigue testing for round specimens[1][2][3].

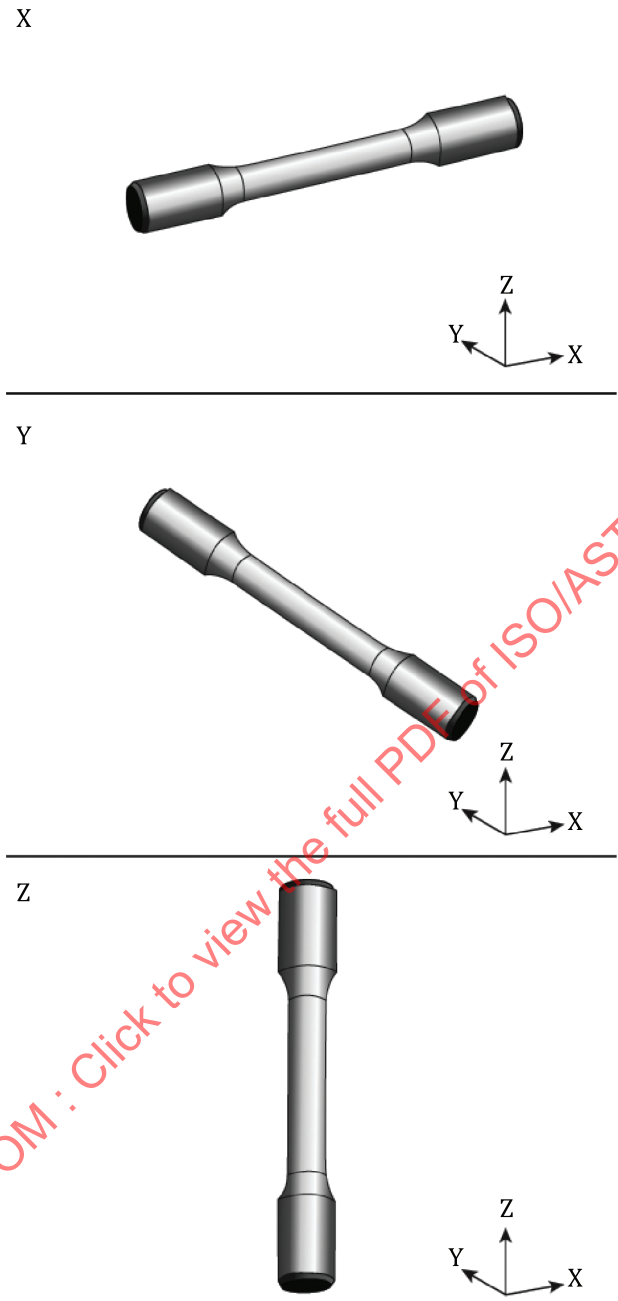



**Figure A.3 — Specimen orientations illustrating possible orientation designation for tensile, low- and high-cycle fatigue testing for round specimens**

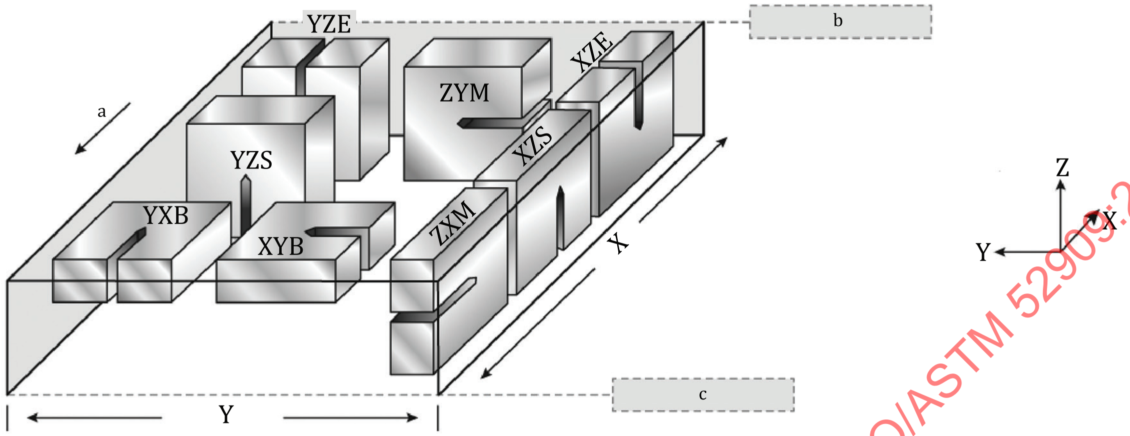


The orientation of the specimen in the build chamber shall be identified by abbreviated orthogonal orientation notation, as specified in ISO/ASTM 52921, where the orientation of the specimen can unambiguously be described by listing only the axis to which the longest dimension runs parallel. These nomenclatures can be used for tests conducted on circular specimen in which there is no starter crack/notch requirement. These test methods are not limited to ASTM E8/E8M and ISO 6892-1 (tensile), ASTM E9 and ISO 4506 (compression) ASTM E466 and ISO 1099 (force-controlled fatigue), and ASTM E606/606M and ISO 12106 (strain-controlled fatigue). For test methods that require a starter crack/notch, see A.4.

NOTE Orientations shown in Figure A.3 are based upon principles of ISO/ASTM 52921. For example, an X specimen designation indicates that the longest dimension is parallel to the X axis and the other two axes have symmetry. The Z axis is always in the build direction.

## A.4 Specimen orientations illustrating crack growth directions with respect to the build direction for fracture toughness and fatigue crack growth testing

Figure A.4 illustrates specimen orientations and crack growth directions with respect to the build direction for fracture toughness and fatigue crack growth testing[1][2][3][4].




**Key**

X X axis
Y Y axis
Z build direction
E end
M middle
S start
B both
a RD, final raster direction.
b End of the build.
c Start of the build.

**Figure A.4 — Specimen orientations illustrating crack growth directions with respect to the build direction for fracture toughness and fatigue crack growth testing**

These nomenclatures can only be used for test methods that require a starter crack/notch in the test specimens (e.g. bend, compact tension, etc.). These test methods are not limited to ASTM E399/E1820 and ISO 12135 (fracture toughness), ASTM E647 and ISO 12108 (fatigue crack growth).

The raster strategy/direction should be reported along with the test report, although there is no direct linkage between the nomenclatures here with raster strategies.



## A.5 Examples of specimen extraction from standard geometries as well as parts to measure location- and orientation-dependent mechanical properties directly

### A.5.1 General

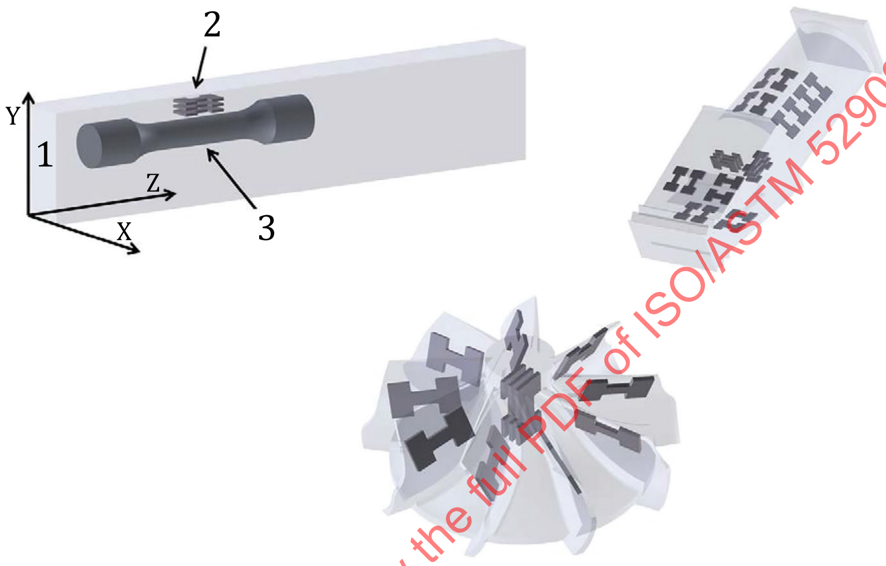
Figure A.5 gives examples of specimen extraction from standard geometries as well as parts to directly measure location and orientation dependent mechanical properties[5][6][7][8].

In the case of specimens excised from complex geometries, a computer-aided design (CAD) figure of the part and a set of coordinate axes should be constructed based on the ISO/ASTM 52921 coordinate systems to record precisely the location and orientation of all the specimens to be extracted. Examples have been provided here as a guidance. For the purpose of this guidance, the build direction is always considered as being parallel to the Z-axis.

### A.5.2 Excised sample

The angle of the excised sample with respect to the build direction should also be reported.

Excised specimen may also be used to document location- and orientation-specific microstructure or defect structure. Various metallographic and non-destructive testing (NDT) techniques may be used on the parts as well as the excised specimen following the same nomenclature outlined presently.




**Key**

1 base

2 excised samples

3 standard geometries

**Figure A.5 — Examples of specimen extraction from standard geometries and parts to directly measure location- and orientation-dependent mechanical properties**

## A.6 Mini-specimens testing approach

### A.6.1 General

In the case of additively manufactured parts, it is often difficult to assess the mechanical properties with the use of standard-sized specimens due to the limited amount of material available. Miniaturized specimens shall be used in cases in which local property measurements are desired in smaller parts with complex shapes. This is important as separate deposition of the "reference" standard-sized specimens can yield misleading and different results from those obtained directly from the AM part because of AM process specifics. This requires preparation of specimens of similar size to the part critical dimensions, with similar deposition orientation, for subsequent material properties assessment.

AM-produced parts can exhibit anisotropy and variable properties along the build height in addition to varying properties with different wall thickness[9][10][11][12]. Characterization of as-built surfaces in addition to, or instead of, conditioned surfaces (e.g. polished, burnished, etc.) should also be considered depending on intended application. In order to provide representative material properties, the samples should be subjected to post-processing that is identical or equivalent to that of the intended final product, before any testing of the material properties is performed.



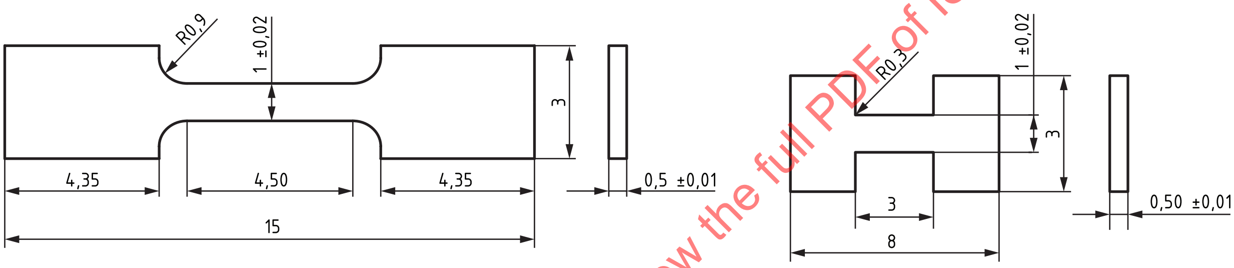
Even if all of the recommendations above are followed, the use of miniaturized specimens shall be highlighted when test results are reported to clearly indicate that non-standard specimens where used.

NOTE This document does not provided recommendations for miniaturized tension testing, resulting in a wide range of sample geometries currently being used. Recent success was reported using the flat sample geometries shown in Figure A.6, where elongation results most consistent with round specimens were obtained using a thickness width ratio ≥0,5[13][14].

If elongation is not a critical property measurement, or the space is very limited, specimens with shorter gauge lengths (see Figure A.6 b) have been used to yield reliable strength properties. From a practical point of view, the minimum recommended gauge length is 3 mm.

The thickness of the specimens should be of about 10 times the grain size to represent "bulk" material behaviour[13]. Based on recent experience summarized in References [13][14][15], a minimum thickness of 0,5 mm is recommended for machined specimens (see Figure A.6). Based on recent experience for near net shape specimens[9][16]. Figure A.7 provides recommended minimum specimen dimensions, although using specimens with larger volume is highly recommended if possible, given the constraints of the build volume. In all cases, the testing and evaluation procedures should comply with ASTM E8/E8M. Strain measurement shall be conducted with measuring systems of appropriate accuracy (video extensometer, laser extensometers, digital image correlation systems, or mechanical extensometer).

Dimensions in millimetres




**a) Proportional specimen (10)** **b) Strain controlled (21)**

**Figure A.6 — Example flat mini tensile specimen geometry**

Dimensions in millimetres

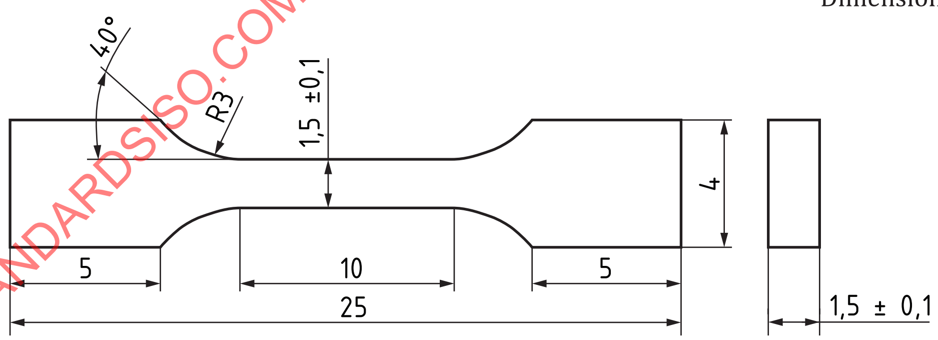



**Figure A.7 — Example of as-built shape specimen geometry (9)**

Miniaturized tensile specimens can also be used for quality control of the AM process, as small specimens (see e.g. Figure A.7) can be built at different locations within each batch. Their small size would not reduce the available "commercial" build space within the chamber and not significantly increase build costs.