Comment Only Ballot #6236

Additively Manufactured Polymer-Based Components for Use in the Petroleum and Natural Gas Industries

API STANDARD 20T

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1 Scope

1.1 Purpose

This standard specifies requirements for qualification of the manufacturing process, production, marking, and documentation of additively manufactured polymer-based components used in the petroleum and natural gas industries when referenced by an applicable API equipment standard or otherwise specified as a requirement for conformance. The qualification process flowchart is shown in Figure 1.

1.2 Applicability

This standard applies to additively manufactured polymer-based components (including composites) produced by material extrusion [also referred to as fused filament fabrication (FFF) or fused deposition modeling (FDM) and fused granulate fabrication (FGF)] and powder bed fusion [also referred to as selective laser sintering (SLS) or multi jet fusion (MJF)].

1.3 Additive Manufacturing Specification Levels (AMSL)

This standard establishes requirements for three additive manufacturing specification levels (AMSL). These three designations—AMSL 1, AMSL 2, and AMSL 3—define increasing levels of additive manufacturing (AM) technical, quality and qualification requirements.

NOTE An AMSL can be assigned to a component by a product specification or standard, the purchaser, or the additive manufacturer.

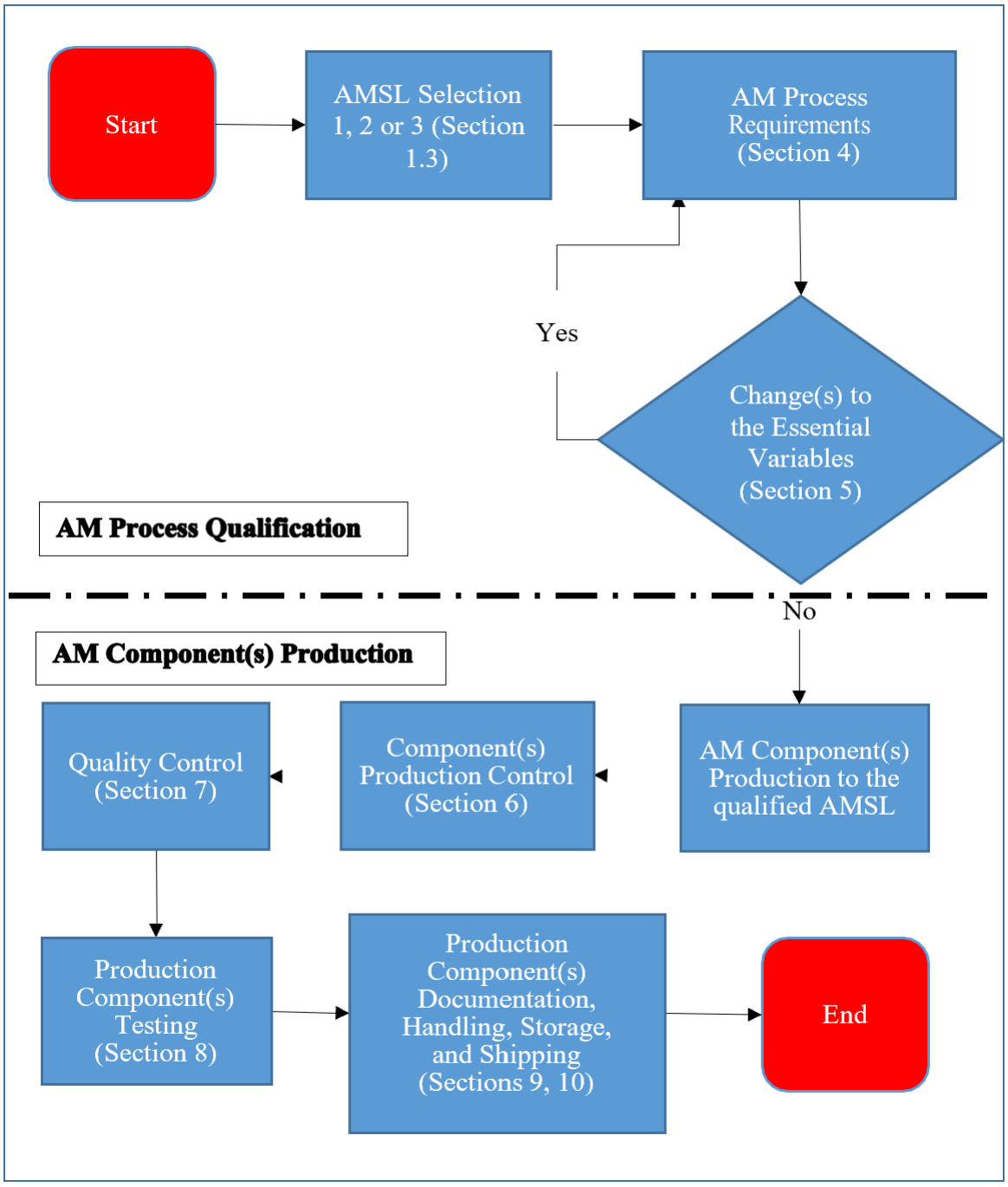

Figure 1—Qualification Process Flowchart

2 Normative References

The following referenced documents are indispensable for the application 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.

API Specification Q1, *Specification for Quality Management System Requirements for Manufacturing Organizations for the Petroleum and Natural Gas Industry*

ANSI[1]/ASQ Z1.4,[2] *Sampling Procedures and Tables for Inspection by Attributes*

ASNT SNT-TC-1A,[3] *Personnel Qualification and Certification in Nondestructive Testing*

ASTM D471,[4] *Standard Test Method for Rubber Property—Effect of Liquids*

ASTM D543, *Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents*

ASTM D638, *Standard Test Method for Tensile Properties of Plastics*

ASTM D790, *Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials*

ASTM D792, *Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement*

ASTM D1238, *Standard Test Method for Melt Flow Rates of Thermoplastics by Extrusion Plastometer*

ASTM D2240, *Standard Test Method for Rubber Property—Durometer Hardness*

ASTM D2583, *Standard Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor*

ASTM D3418, *Standard Test Method for Transition Temperatures and Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimetry*

ASTM D4000, *Standard Classification System for Specifying Plastic Materials*

ASTM D6980, *Standard Test Method for Determination of Moisture in Plastics by Loss in Weight*

ASTM E1131, *Standard Test Method for Compositional Analysis by Thermogravimetry*

ISO 9001,[5] *Quality management systems — Requirements*

ISO 9712, *Non-destructive testing — Qualification and certification of NDT personnel*

ISO 10005, *Quality management — Guidelines for quality plans*

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[1] American National Standards Institute, 1899 L Street, NW, Washington, DC 20036, www.ansi.org.

[2] American Society for Quality, P.O. Box 3005, Milwaukee, Wisconsin 53201-3005, www.asq.org.

[3] American Society for Nondestructive Testing, P.O. Box 28518, 1711 Arlingate Lane, Columbus, Ohio 43228, www.asnt.org.

[4] ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428, www.astm.org.

[5] International Organization for Standardization, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, www.iso.org.

ISO 23936 *(all components) Petroleum, petrochemical and natural gas industries — Non-metallic materials in contact with media related to oil and gas production*

ISO/ASTM 52900, *Additive manufacturing — General principles — Terminology*

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

NORSOK M-710,[6] *Qualification of non-metallic materials and manufacturers — Polymers*

SAE AMS7100 (2019),[7] *Process Specification and Material for Fused Filament Fabrication*

3 Terms, Definitions, Acronyms and Abbreviations

3.1 Terms and Definitions

For the purposes of this document, the terms and definitions given in ISO/ASTM 52900 and the following apply. Where identical terms and definitions are given, the terms and definitions provided in this specification supersede the terms and definitions contained in ISO/ASTM 52900.

3.1.1
acceptance number
The maximum number of defects or defective units in the sample that will permit acceptance of a lot or batch.
3.1.2
additive manufacturer
An entity that fabricates the additively manufactured components.
3.1.3
build
See “build cycle” in ISO/ASTM 52900.
3.1.4
by agreement
agreed between the additive manufacturer and the purchaser.
3.1.5
certificate of conformance
CoC
A document containing the statement by the additive manufacturer certifying that the component(s) meets the requirements of this standard.
3.1.6
component build file
A file that defines the geometry and arrangement of the components, witness specimens, and support structures, as applicable, that will be built by printing equipment.
NOTE This file will be converted to printing instructions.

3.1.7
first article
A new component or a component with a revised design (drawing, material, manufacturing equipment, etc.) or a new manufacturing location.

[6] Standards Norway, P.O. Box 242, NO-1326, Lysaker, Norway, www.standard.no.

[7] SAE International, 400 Commonwealth Drive, Warrendale, Pennsylvania 15096, www.sae.org.

3.1.8
feedstock
Bulk raw material supplied to the additive manufacturing building process.
3.1.9
feedstock lot
The quantity of feedstock produced under traceable, controlled conditions, from a single manufacturing process cycle.
3.1.10
feedstock supplier
The provider of material/feedstock to be processed in the additive manufacturing system.
NOTE Typically, it is the feedstock manufacturer.

3.1.11
material extrusion
An additive manufacturing process in which material is selectively dispensed through a nozzle orifice.
3.1.12
on-site
The additive manufacturer's facility.
3.1.13
powder bed fusion
An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.
3.1.14
printing equipment
See "AM Machine"' in ISO/ASTM 52900.
3.1.15
process consumables
Material inputs to the additive manufacturing process that are specified in accordance with the item being manufactured (e.g. feedstock, substrate, as applicable to the process used).
3.1.16
production lot
All components of the same build with the same post-processing.
3.1.17
removable components
Items that are removed/replaced as components of the manufacturing process (e.g. build platform, recoater blade).
3.1.18
serviceable components
Items that are removed/replaced/cleaned as components of a maintenance event (e.g. filters, lenses, laser).
3.1.19
substrate
The surface onto which the initial layer of feedstock is deposited. This may be a build platform (e.g. for PBF), a surface that becomes an integral portion of the component, or a surface of an existing component.

3.2 Acronyms and Abbreviations

For the purposes of this standard, the following abbreviations apply.

3MF tridimensional manufacturing format
AM additive manufacturing
AMF additive manufacturing file format
AMSL additive manufacturing specification level
CAD computer-aided design
CoC certificate of conformance
CT computed tomography
DMA dynamic-mechanical analysis
DPD digital product definition
DSC differential scanning calorimetry

FDM fused deposition modeling
FFF fused filament fabrication
FGF fused granulate fabrication
FTIR Fourier transform infrared
IGES initial graphics exchange specification
NDE nondestructive examination
MEx material extrusion
MFI melt flow index
MJF multi jet fusion
MPS manufacturing process specification
NCR nonconformance report
OEM original equipment manufacturer
PBF powder bed fusion
QMS quality management system
SDS safety data sheet.
SEC size-exclusion chromatography
SLS selective laser sintering
STEP standard for the exchange of product model data
T_g glass transition temperature
TGA thermal-gravimetric analysis
T_m melting temperature
X_c degree of crystallinity

4 Requirements for the Additive Manufacturing Process

4.1 General

Material extrusion (MEx) and powder bed fusion (PBF) processes are covered in this section of the document. Other processes can be included by agreement; therefore, the additive manufacturer shall develop a specification aligned with this document's requirements as applicable.

This standard gives the requirements for three additive manufacturing specification levels (AMSL). The following subparagraphs describe the conditions which, when met, allow the additive manufacturing (AM) process to receive the appropriate AMSL classification.

When additively manufactured polymer-based components are ordered to an API product specification or API product standard, the functional requirements shall fulfill the API product specification or API product standard. The qualification requirements shall be by agreement for non-API standard products.

4.2 Additive Manufacturer

4.2.1 General

For all AMSLs, the additive manufacturer shall implement and maintain required controls to ensure that the product and services meet specified requirements and shall conform with the requirements of 4.2 and its subsections.

4.2.2 Additive Manufacturer Quality Management System (QMS)

The additive manufacturer shall establish, document, implement, and maintain a QMS and associated processes. The QMS shall be in conformance with either API Specification Q1 or ISO 9001.

The additive manufacturer shall define their internal audit requirements for processes covered by this standard to ensure that these processes achieve planned results.

4.2.3 Quality Control Procedures

All quality control activities shall be controlled by the additive manufacturer's documented procedures, which include appropriate methodology and acceptance criteria.

Nondestructive examination (NDE) procedures shall be detailed regarding the requirements of all applicable nationally or internationally recognized standards specified by the additive manufacturer. All NDE procedures shall be approved by a Level III examiner qualified in accordance with ASNT SNT-TC-1A or ISO 9712 in the specified discipline.

4.2.4 Technical Review Requirements

The additive manufacturer shall maintain procedure(s) to ensure that technical requirements are reviewed prior to acceptance of the order.

The additive manufacturer shall maintain records of this review, including:

- applicable purchaser or governing design and construction specifications/standards;
- deviations from governing design and/or construction specifications/standards;
- material specifications;
- acceptance criteria;
- qualification of procedures;
- qualification of personnel;
- qualification of printing equipment;
- outsourced services;
- inspection and testing requirements, including third-party verification;
- identification and traceability; and
- post-processing requirements.

4.2.5 Personnel Training and Competency Requirements

Personnel shall be competent to carry out assigned tasks/responsibilities based on the appropriate education, training, skills, and experience needed to meet product and purchase order requirements. A written procedure shall define personnel competency and identify training and qualification requirements.

The additive manufacturer shall identify:

- methods required for personnel training qualifications;
- knowledge and training necessary to address specific requirements;
- qualifications required for personnel performing processes that require validation; and
- method(s) used to verify the continued competency of personnel based on roles.

The additive manufacturer shall maintain evidence of conformity to the above requirements.

4.2.6 Nondestructive Examination Personnel Requirements

Personnel performing NDE shall be qualified in accordance with the additive manufacturer's documented training program and procedures that are based on the requirements specified in the following:

- ISO 9712; or
- ASNT SNT-TC-1A; or
- an equivalent nationally or internationally recognized standard.

NDE Level I or Level II personnel shall be qualified by NDE Level III personnel in the specified discipline.

4.2.7 Visual Inspection Personnel Requirements

Personnel performing visual inspection for acceptance shall take and pass an annual vision examination in accordance with the additive manufacturer's documented procedure that is based on the requirements specified in the following:

- ISO 9712; or
- ASNT SNT-TC-1A; or
- an equivalent nationally or internationally recognized standard.

4.2.8 Other Personnel Requirements

All other personnel performing measurements, inspections, or tests for acceptance shall be qualified in accordance with the additive manufacturer's documented procedures and requirements.

4.2.9 Facility Requirements

The additive manufacturer shall have on-site equipment and personnel to perform the required processes needed to produce the components under the scope of this standard as identified below:

- equipment to perform required printing activities (excluding post-processing activities);
- storage and usage of process consumables and equipment in accordance with the requirements of this standard;
- appropriate handling and lifting equipment (as applicable); and
- inspection and test equipment (as applicable).

4.3 Feedstock Requirements

4.3.1 Feedstock Suppliers

The feedstock supplier shall maintain a quality management system that, at a minimum, conforms to ISO 9001.

Feedstock lots shall be supplied with the following documentation:

- feedstock vendor name;
- material identification;

- lot number;
- date of manufacture;
- shelf life;
- certificate of conformance (CoC).

The filament spool or container (filament or powder/granulate) shall have a unique alphanumeric identifier.

4.3.2 Filament Feedstock

The additive manufacturer's specification shall include requirements and acceptance criteria for the properties described in Table 1 and determined per the applicable specification or an equivalent internationally recognized standard.

Table 1—Minimum Requirements to be Defined in the Filament Feedstock Specification

Property			Documentation[a]	Quality Control[b]
Item	**Description**	**Standard**		
General Information				
1	Classification			
1.a	Material/Filler type and grade[c,d]	ASTM D4000	D	—
1.b	Filler amount (TGA)	ASTM E1131 F. Supplier[e]	D	—
Dimensions[e]				
2	Diameter			—
2.a	Diameter average	F. Supplier[e]	D	QC
2.b	99.73 % of diameter readings in range	F. Supplier[e]	D	QC
2.c	Diameter min.	F. Supplier[e]	D	QC
2.d	Diameter max.	F. Supplier[e]	D	QC
3	Ovality	F. Supplier[e]	D	QC
Rheological Characteristics				
4	Melt flow index (MFI)	ASTM D1238	D	QC
Physical Properties				
5	Hardness[g]	4.5.4.5	D	—
6	Density (Specific Gravity)	4.5.4.6	D	QC
7	Moisture	ASTM D6980	D	QC[f]
Thermal Properties[h]				
8	Glass transition (T_g) by DSC	4.5.4.2	D	—
9	Melting point (T_m) by DSC	4.5.4.2	D	—
10	Crystallinity (X_c) by DSC	4.5.4.2	D	—
Mechanical Properties[g,i]				
11	Tensile yield stress, maximum stress, modulus, strain at break at (73 ± 4) °F:	4.5.4.4.1	D	—
12	Flexural modulus and strength at (73 ± 4) °F	4.5.4.4.2	D	—

[a] Properties to be documented for each supplier and compound (filament data sheet).

[b] Properties to be reported on lot-wise basis according to QC procedures.

[c] In case the resin type is not included in ASTM D4000, abbreviations known in the industry shall be used.

[d] In case there is a mix of resin, the name should reflect the "blend" with major components.

[e] According to the feedstock supplier's procedures.

[f] Some materials are hydroscopic. The material specification shall specify the feedstock moisture content requirement at the moment of the additive manufacturing process.

[g] The additive manufacturer shall document the properties on test coupons obtained from each of the printing equipment, if applicable.

[h] Melting point and crystallinity only apply for semi-crystalline thermoplastic materials.

[i] Test specimens prepared by the additive manufacturer in each of the orthogonal orientation notation according to ISO/ASTM 52921.

4.3.3 Powder/Granulate Feedstock

The additive manufacturer's specification shall include requirements, frequency, and acceptance criteria for the parameters described in Table 2 and determined per the applicable specification or an equivalent internationally recognized standard.

Table 2—Minimum Requirements to be Defined in the Powder/Granulate Feedstock Specification

Property			Documentation[a]	Quality Control[b]
Item	**Description**	**Standard**		
General Information				
1	Classification			
1.a	Material/Filler type and grade[c,d]	ASTM D4000	D	—
1.b	Filler amount (TGA)	ASTM E1131 F. Supplier[e]	D	—
Particle Size and Distribution[e]				
2	Size	F. Supplier[e]	D	QC
3	Distribution	F. Supplier[e]	D	QC
Rheological Characteristics				
4	Melt flow index (MFI)	ASTM D1238	D	QC
Physical Properties				
5	Hardness[g]	4.5.4.5	D	—
6	Density (Specific Gravity)	F. Supplier[e]	D	QC
7	Moisture	ASTM D6980	D	QC[f]
Thermal Properties[h]				
7	Glass transition (T_g) by DSC	ASTM D3418	D	—
8	Melting point (T_m) by DSC	ASTM D3418	D	—
9	Crystallinity (X_c) by DSC	ASTM D3418	D	—
Mechanical Properties[g,i]				
10	Tensile yield stress, maximum stress, modulus, strain at break at (73 ± 4) °F:	ASTM D638	D	—
11	Flexural modulus and strength at (73 ± 4) °F	ASTM D790	D	—

[a] Properties to be documented for each supplier and compound (powder data sheet).

[b] Properties to be reported on lot-wise basis according to QC procedures.

[c] In case the resin type is not included in ASTM D4000, abbreviations known in the industry shall be used.

[d] In case there is a mix of resin, the name should reflect the "blend" with major components.

[e] According to the feedstock supplier's procedures.

[f] Some materials are hydroscopic. The material specification shall specify the feedstock moisture content requirement at the moment of the additive manufacturing process.

[g] The additive manufacturer shall document the properties on test coupons obtained from each of the printing equipment, if applicable.

[h] Melting point and crystallinity only applies for semi-crystalline thermoplastic materials.

[i] Test specimens prepared by the additive manufacturer in each of the orthogonal orientation notation according to ISO/ASTM 52921.

4.3.4 Feedstock Recycling and Reuse

The additive manufacturer shall verify that the components manufactured using blends of new and recycled material fulfill the requirements of this document.

The feedstock supplier and additive manufacturer shall maintain a documented procedure for material recycling and end-of-life processing for the feedstock material. Recycled material from the same production system shall be used and meet the same requirements as a virgin material compound.

4.3.5 Storage

If a specified maximum moisture level is required for the filament feedstock, the spool shall be sold in sealed packaging. Also, the supplier shall provide recommended storage conditions. If needed, the additive manufacturer shall dry the filament spool following their procedures before it is used in the manufacturing equipment.

If a feedstock of powder has a recommended moisture level, the powder shall be dried following the additive manufacturer's procedure before being used in the manufacturing equipment.

4.3.6 Materials Handling and Packaging

Feedstock shall be stored in containers according to the feedstock supplier’s instructions, including but not limited to the shelf life at specified storage conditions and the safety data sheet (SDS). Procedures shall be established to prevent contamination of the filament during handling.

The material shall be packaged in such a way that the feedstock can dispense with a uniform force. The container shall be labeled with following information at a minimum. This label and information shall be visible and easily read.

- name;
- component number or product designation;
- lot number;
- date of manufacture;
- feedstock manufacturer location;
- API 20T.

4.3.7 Traceability

Each material container shall be given a unique serial number that is tied to a specific manufacturing lot. That manufacturing lot number shall be tied to individual raw component lots and manufacturing processes. The recording and retention of this data shall be defined by the feedstock supplier’s QMS.

4.3.8 Rejection

Feedstock not conforming to this specification and the applicable additive manufacturer's specifications shall be subject to rejection.

4.4 Additive Manufacturing Printing Equipment

4.4.1 General

The additive manufacturer shall maintain AM printing equipment procedures that address requirements and the following for MEx and PBF, as applicable:

- operation and calibration;
- qualification geometry(s) and associated test plan (including acceptance criteria);
- essential variables as defined in Section 5.

4.4.2 Preventative Maintenance Plan

For all AMSLs, the additive manufacturer shall maintain a preventative maintenance plan that covers the AM printing equipment (including a schedule) and addresses the following for MEx and PBF, as applicable:

- climate control requirements (e.g. temperature and humidity) and recorded history;
- power supply requirements, which are defined and verified during installation and ongoing servicing (installation certificate and service reports shall be retained by the additive manufacturer);
- instructions for the cleaning of the AM printing equipment, associated tools, and auxiliary equipment (non-contaminating cleaning solutions for the equipment shall be used);
- cleaning/purging and inspection requirements for the AM printing equipment (including frequency of cleaning and definition of events that would require cleaning to be performed, such as a material changeover from one feedstock material grade to another;
- requirements for the maintenance and inspection of serviceable components and removable components;
- calibration requirements and calibration record history shall be maintained for printing and auxiliary equipment, such as the heated chamber and the post-processing oven;
- If applicable, air or gas supply system requirements, where used, that shall be in accordance with the AM printing equipment manufacturer instructions (e.g. for pressure, temperature, flow rate, cleanliness).

4.4.3 Qualification Records

AM printing equipment qualification records shall include:

- additive manufacturer facility name and address;
- printing equipment manufacturer and model;
- printing equipment serial number;
- software/firmware versions;
- operator qualification record;

- qualifying test build records, including geometry, values of the essential variables (as defined in Section 5), and test results;
- test results of the mechanical properties as requested in Table 1 and Table 2.

4.5 First Article

4.5.1 General

The first article shall be manufactured with the same manufacturing process specification (MPS) as the production components, in accordance with 6.2.

4.5.2 Digital Product Definition File

The digital product definition (DPD) file collects all the data required to reproduce an additively manufactured polymer component.

The additive manufacturer shall have a documented procedure to develop and maintain the DPD file that includes the digital data required to manufacture the additively manufactured component. At a minimum, the DPD file shall include, as applicable:

- geometry component files (e.g. CAD, STL, AMF, 3MF, STEP, IGES);
- component build file (including orientation and supports);
- slicing strategy: slicer settings file;
- operative code for the equipment: equipment instruction file;
- software used: a record of all versions of all software used to produce the files listed above;
- heating and cooling strategy.

The additive manufacturer shall have a procedure to ensure the integrity of the DPD file and shall maintain records of the revision history of the DPD.

4.5.3 First Article Test Requirements

4.5.3.1 General

The first article shall be manufactured in accordance with the same DPD and MPS of the production component. When using a DPD that contains multiple components, each of the components shall be categorized as the first article. Each component can be categorized with a different AMSL.

The additive manufacturer shall evaluate the first articles according to the requirements defined in Table 3 for MEx and Table 4 for PBF.

The additive manufacturer shall document the required test results and develop their QA/QC criteria based on this evaluation; therefore, the additive manufacturer shall validate that the number of test specimens are a statistical representation of the first article.

For AMSL 1 and 2, the destructive testing to assess the first article material properties shall be performed by using test specimens extracted/machined from prolongations or printed concurrently. The test specimens shall be co-located in the build with the first article on the same build plate and subjected to the same thermal-post-production processing, if required.

For AMSL 3, the first article shall be used as a sacrificial component to extract test specimen(s). Under some circumstances (e.g., article size or unique configuration), the article shall be used as the test specimen; therefore, a statistical representation of the components shall be printed. By agreement, the properties of the first article may be assessed by using specimen(s) as described for AMSL 1 and 2.

NOTE In some instances, it may be prudent to subject the test specimens not only to the thermal treatment, but to any additional post-fabrication steps imparted to the first article that could impact the material properties.

Table 3—Test Requirements for the First Article—MEx

Test Sample Configuration	Parameter[a] (Test Procedure)	AMSL 1	AMSL 2	AMSL 3
Specimens	Fingerprint (4.5.4.2)	—	—	Required
	Thermal Properties and Crystallinity (4.5.4.3)	—	—	Required
	Mechanical Properties[b] (4.5.4.4)	1 set in the Z orientation 1 set 90° from Z orientation	1 set in the Z orientation 1 set 90° from Z orientation	2 set in the Z orientation 2 set 90° from Z orientation
	Hardness (4.5.4.5)	—	—	Required
	Specific Gravity (4.5.4.6)	Required	Required	Required
	Porosity (4.5.4.7)	Required	Required	Required
	Visual Inspection—Macro (4.5.4.8.1)	Required	Required	Required
Component in the final condition	Visual Inspection—Macro (4.5.4.8.1)	Required	Required	Required
	Dimensional Inspection (4.5 4.9)	Required	Required	Required
	Performance Test (4.5.4.10)	—	—	Required
	Specific Gravity (4.5.4.6)	—	—	Required
	Porosity (4.5.4.7)	—	—	Required
	NDE (4.5.4.8.2)	—	—	Required

[a] Additional testing may be required by agreement depending on the component functionality. See Annex C.

[b] Test specimens prepared by the additive manufacturer in each of the orthogonal orientation notation according to ISO/ASTM 52921

Table 4—Test Requirements for the First Article—PBF

Test Sample Configuration	Parameter[a] (Test Procedure)	AMSL 1	AMSL 2	AMSL 3
Specimens	Fingerprint (4.5.4.2)	—	—	Required
	Thermal Properties and Crystallinity (4.5.4.3)	—	—	Required
	Mechanical Properties[b] (4.5.4.4)	1 set in the Z orientation 1 set 90° from Z orientation	1 set in the Z orientation 1 set 90° from Z orientation	2 set in the Z orientation 2 set 90° from Z orientation
	Hardness (4.5.4.5)	—	—	Required
	Specific Gravity (4.5.4.6)	Required	Required	Required
	Porosity (4.5.4.7)	Required	Required	Required
	Visual Inspection—Macro (4.5.4.8.1)	Required	Required	Required
Component in the final condition	Visual Inspection—Macro (4.5.4.8.1)	Required	Required	Required
	Dimensional Inspection (4.5 4.9)	Required	Required	Required
	Performance Test (4.5.4.10)	—	—	Required
	Specific Gravity (4.5.4.6)	—	—	Required
	Porosity (4.5.4.7)	—	—	Required
	NDE (4.5.4.8.2)	—	—	Required

[a] Additional testing may be required by agreement depending on the component functionality. See Annex C.

[b] Test specimens prepared by the additive manufacturer in each of the orthogonal orientation notation according to ISO/ASTM 52921

4.5.3.2 Integrated Substrate

When the substrate is integrated within the final component, or two or more material grades are used to manufacture an article, the additive manufacturer shall confirm that the mechanical and physical properties at the interface between the substrate and the deposited material (or between two material grades) are in accordance

with the requirements of the applicable material specification, product specification, and MPS. The substrate used for the qualification shall be representative of the substrate used in production.

In addition to the test requirements defined in Table 3 for MEx and Table 4 for PBF, the pieces manufactured using an integrated substrate or material combinations shall fulfill the requirements reported in Table 5.

Table 5—Test Requirements for the First Article—Integrated Substrate

Test Sample Configuration	Parameter (Test Procedure)	AMSL 1	AMSL 2	AMSL 3
Integrated Substrate	Visual Inspection (Pre-build)—Macro (4.5.4.8.1)	Required	Required	Required
	Visual Inspection—Cross-section Examination (4.5.4.8.2)	Required	Required	Required
	Structural Performance (4.5.4.10)	Required	Required	Required
	Interphase Adhesion Resistance (4.5.4.4.3)	—--	Required	Required

4.5.4 Material Testing

4.5.4.1 General

All material tests shall be performed according to the requirements in Table 3 and Table 4 after thermal post-processing steps (that can affect material properties as stated in the applicable material specification, product specification, and/or MPS) have been performed.

NOTE For thermoplastics, material types can be amorphous and require no thermal post-processing, or can be semicrystalline and undergo in-process annealing within the build chamber or post annealing after printing.

4.5.4.2 Fingerprint

For AMSL 3, the chemical structure fingerprint of the first article shall be documented by using Fourier transform infrared (FTIR) in accordance with a nationally or internationally recognized standard. The sample preparation and method selected shall be clearly described and documented.

4.5.4.3 Thermal Properties and Crystallinity

For AMSL 3, the thermal transitions of the first article, T_g and T_m, shall be documented depending on the material characteristics and molecular arrangement (semi-crystalline vs. amorphous). The properties shall be determined using DSC in accordance with ASTM D3418 or an equivalent internationally recognized standard. In the case of semi-crystalline polymers, the degree of crystallinity (X_c) shall be also documented.

4.5.4.4 Mechanical Properties

4.5.4.4.1 General

The mechanical properties, either tensile or flexural, of the first article shall be documented. A minimum of five specimens shall be tested. The test direction according to the orthogonal orientation notation in ISO/ASTM 52921 shall be documented.

NOTE For thermoplastics, material types can be amorphous and require no thermal post-processing, or can be semicrystalline and undergo in-process annealing within the build chamber or post annealing after printing. For thermosets, post-processing may or may not be required.

4.5.4.4.2 Tensile Properties

Tensile tests shall be performed in accordance with the procedures specified in ASTM D638 or an equivalent internationally recognized standard, and the following parameters shall be reported, as applicable:

- yield strength and strain;
- ultimate tensile strength and strain;
- modulus of elasticity.

4.5.4.4.3 Flexural Properties

Flexural tests shall be performed in accordance with the procedures specified in ASTM D790 or an equivalent internationally recognized specification, and the following parameters shall be reported, as applicable:

- flexural modulus;
- flexural strength.

4.5.4.4.4 Adhesion Properties

The additive manufacturer shall define the test methodology to document the adhesion properties between the substrate and the deposited material or between two materials. The test method depends on the article configuration and the arrangement of layers.

4.5.4.5 Hardness Testing

Shore hardness testing shall be conducted in accordance with applicable procedures specified in ASTM D2240 or an equivalent internationally recognized standard. Alternatively, testing in accordance with ASTM D2583 or an equivalent internationally recognized standard can be used to measure material hardness. Surface finishing can impact the hardness values; therefore, the additive manufacturer shall verify that this property is applicable for component surface finish. Otherwise, a technical justification shall be documented.

4.5.4.6 Specific Gravity

Specific gravity measurement and reporting shall be according to ASTM D792 or an equivalent internationally recognized standard. The measurement shall be performed and documented on representative coupon or prolongation, printed, and processed alongside the first article after the final thermal processing step. For AMSL 3, the test coupon shall be the article or a coupon extracted from the first article.

4.5.4.7 Porosity

The porosity shall be evaluated after an examination of several cross-section cuts of test specimens. The additive manufacturer shall develop a procedure to document the porosity level and acceptance criteria. The cross-section examination requires the aid of magnifier equipment (microscopy). This is considered a destructive examination.

NDE may also be used to determine the porosity in the material; however, it should be calibrated against the destructive evaluation for the first article.

4.5.4.8 Nondestructive Examinations

4.5.4.8.1 Visual Inspection

Visual inspection of components in the as-built and finished components shall be performed in accordance with the additive manufacturer's written specification. Table 1 from SAE AMS7100 lists imperfections generally inherent in the MEx process. The additive manufacturer shall have the visual inspection requirements in a written specification for the MEx and PBF processes.

4.5.4.8.2 Volumetric NDE

The entire volume of the component, as far as practical, shall be volumetrically inspected after completion of thermal post-processing and prior to machining operations that limit effective interpretation of the results of the examination. When no thermal post-processing is specified, volumetric NDE shall be performed on the component in the as-printed condition.

Volumetric NDE methods shall be in accordance with the applicable material specification and/or API product specification. X-ray, microwave, and ultrasonic are considered the primary NDE technologies used to evaluate polymer-based components.

The additive manufacturer shall develop a NDE procedure and acceptance criteria. Acceptance criteria shall be in accordance with relevant design and material specifications as stated in the applicable material specification and/or API product specification.

NDE shall be conducted on the same articles used for the structural testing. A post evaluation of these articles shall be conducted to validate the NDE results.

4.5.4.9 Critical Dimensional Inspection

Critical dimensions shall be specified and inspected.

Acceptance criteria shall be in accordance with relevant design and material specifications as stated in the applicable material specification and/or API product specification.

NOTE Where critical internal geometries and features cannot be verified using traditional inspection methods, CT scanning may be used to verify dimensional conformance.

4.5.4.10 Performance Test

The performance test shall be conducted according to the additive manufacturer's written procedure and is intended to verify the mechanical response of the component by following any of these approaches:

- stand-alone component testing;
- device simulating the component operating conditions;

— following any specific standard that regulates the functionality of the component.

4.5.5 First Article Post-build Processing

Post-build processing for the first article shall be in accordance with 6.6.

5 Limits on the Qualification of the Additive Manufacturing Process

5.1 General

AM process variables shall be controlled and reported to the purchaser as indicated in 5.2 and 5.3.

Any change to variables in Table 6 from the originally qualified first article require requalification of the first article. The requalification shall use parameters incorporating the altered variables and shall be documented. The requirements of the requalification shall be as specified for the applicable AMSL in Section 4.

Where a previously qualified parameter meets the requirements of a modified essential variable specification included in Table 4, no requalification is required. In addition, no requalification is needed for non-essential AM variables (see Annex A).

5.2 Essential Additive Manufacturing Variables to be Reported

For MEx and PBF, Table 6 defines the AM variables that are reported to the purchaser, and any changes to them (according to the applicable AMSL) require first article requalification in accordance with Section 4.

Table 6—MEx and PBF Essential Additive Manufacturing Variables to be reported (as applicable)

Parameter	Applicable AMSL	
	MEx	PBF
Specified feedstock compound	1, 2, 3	1, 2, 3
Specified powder particle size and distribution	N/A	2, 3
Specified filament diameter and type	1, 2, 3	N/A
Specified post-processing heat treatment and other thermal processes	1, 2, 3	1, 2, 3
Printing machine manufacturer and model number	1, 2, 3	1, 2, 3
Name and revision number of the DPD	1, 2, 3	1, 2, 3
Printing machine ID	3	3 (requalification by agreement)
Energy source ID	3	3

5.3 Essential Additive Manufacturing Variables Not Reported

For MEx and PBF, Table 7 defines the AM variable values that are not required to be reported to the purchaser; however, the purchaser shall be notified of any changes to them (according to the applicable AMSL), and the first article shall be requalified in accordance with Section 4.

Table 7—MEx and PBF Essential Additive Manufacturing Variables Not Reported (as applicable)

Parameter	Applicable AMSL	
	MEx	PBF
Feedstock storage variables	1, 2, 3	1, 2, 3
Specified humidity of chamber atmosphere	—	1, 2, 3
Printing machine physical location	requalification by agreement	requalification by agreement
Printing machine software/firmware version	1, 2, 3	1, 2, 3
Feedstock production method	1, 2, 3	1, 2, 3
Programmed layer height	1, 2, 3	1, 2, 3
Modifications to the energy delivery system	1, 2, 3	1, 2, 3
Chamber heat temperature setpoint or distribution	1, 2, 3	1, 2, 3

6 Components Production Control

6.1 General

Once the AM process is qualified in accordance with Section 4, the production of additively manufactured polymer-based components shall conform to the requirements of Sections 6, 7, and 8.

6.2 Manufacturing Process Specification

The additive manufacturer shall have a MPS that details the sequence of steps of the AM process for each build. The MPS shall contain the sequence of operations and, at a minimum, shall address the following:

- applicable AMSL;
- DPD file and revision;
- pre-build check (see 6.3);
- post-processing activities, such as heat treatment, machining, and others;
- quality control and inspection requirements (see Section 7);
- documentation requirements (see Section 9);
- heating and cooling strategy, when not included in the DPD.

Inspection and test plans shall be developed in accordance with the guidelines provided in ISO 10005.

6.3 Pre-Build Check

The additive manufacturer shall maintain a documented pre-build check procedure. The procedure shall include verification of the following, as applicable:

- machine status, including maintenance, qualification, and calibration;
- feedstock specification, expiration date, and quantity necessary to complete the build;

- build plate/substrate;
- shielding gas;
- cleanliness of nozzle;
- feeder system;
- build chamber cleanliness;
- build chamber environment;
- DPD file;
- MPS.

6.4 Batch Control/Powder Recycling

The additive manufacturer shall conform with the requirements of 4.3.4.

6.5 Process Interruptions

The additive manufacturer shall maintain a documented procedure for the control of build interruptions and shall address both planned and unplanned interruptions.

Records on unplanned process interruptions shall be submitted to the purchaser. Resolution of unplanned interruption nonconformance reports (NCR) shall be according to the applicable MPS.

Planned build interruptions shall be performed in accordance with the applicable MPS. Records of build interruptions shall be maintained.

6.6 Post-build Processing

6.6.1 General

Post-build processing shall be performed in accordance with the applicable MPS. Post-build activities can include but are not limited to processes such as curing, de-powdering, stress relieving, heat treatment, and machining.

The temperature, hold times, component placement, and load size for post-production processing for stress-relief, mechanical properties, and morphology shall be selected based on the specific requirements for the component.

6.6.2 Stress Relief

Stress-relieving operations shall be performed in accordance with the applicable design and material specifications as stated in the MPS. The additive manufacturer shall maintain a documented procedure for the stress-relieving process.

All stress-relief operations shall be performed using equipment with verified maintenance and calibration records.

6.6.3 Heat Treatment

Time at temperature and details of thermal cycles shall conform with the material specifications for the specific materials used in the component build. Heat treatment ovens shall be calibrated in accordance with the additive manufacturer's procedure.

All heat treatment operations shall be performed using equipment with verified maintenance and calibration records.

6.6.4 Curing, De-powdering, and De-binding/Sintering

The additive manufacturer shall maintain a documented procedure for the curing, de-powdering, and de-binding/sintering processes.

Curing, de-powdering, and de-binding/sintering shall be performed using equipment with verified maintenance and calibration records.

6.7 Marking and Identification of Production Components

All components shall be identified as follows:

- "API 20T-1" for AMSL 1;
- "API 20T-2" for AMSL 2;
- "API 20T-3" for AMSL 3.

Specific part-marking methods and marking locations shall be by agreement.

7 Quality Control

7.1 General

This section specifies the minimum quality control requirements for polymer-based components manufactured to meet this standard. The additive manufacturer shall have a quality management system (QMS) in accordance with 4.2.2.

7.2 Monitoring and Measuring Equipment

Instruments used to measure and control critical process variables during the AM process, including all post-processing activities, shall be serviced and calibrated in accordance with written specifications.

Equipment used to inspect, test, or examine materials or other equipment shall be identified, controlled, calibrated, and adjusted at specified intervals in accordance with documented instructions, and consistent with nationally or internationally recognized standards, to maintain the accuracy required by this standard.

7.3 Quality Control Procedures

All quality control activities shall be controlled by the additive manufacturer's documented procedures, which include appropriate methodology and acceptance criteria.

NDE procedures shall be detailed regarding the requirements of all applicable nationally or internationally recognized standards specified by the additive manufacturer.

All NDE instructions shall be approved by a Level III examiner, qualified as per applicable standards in 4.2.6. Acceptance criteria and selection of NDE methods must be agreed upon between the additive manufacturer and the purchaser.

7.4 Sampling

Where sampling in Table 9 and Table 10 is specified, Table 8 shall apply. Samples selected from production lots shall be random. The acceptance number, as defined in ANSI/ASQ Z1.4, shall be zero.

Table 8—Sampling

Lot Size	Sample Size
2 to 8	All
9 to 50	8
51 to 90	13
91 to 150	20
151 to 280	32
281 to 500	50
501 to 1200	80
Based on ANSI/ASQ Z1.4 Table 1, General inspection level II. NOTE Sampling can be adjusted by agreement.	

7.5 Quality Control Personnel Requirements

All other personnel performing measurements, inspections, or tests for acceptance shall be qualified in accordance with the additive manufacturer's documented procedures and requirements. Personnel performing NDE and visual inspection shall be qualified according to the requirement in 4.2.5.

8 Production Components Quality Control Requirements

8.1 General

This section describes the inspection and testing requirements as defined in Table 9 and Table 10 for production of additively manufactured polymer-based components, depending on the applicable AMSL.

For MEx and PBF processes, separate DPD(s) may be required to obtain test specimens for material testing in accordance with this section due to geometry limitations. Test specimens shall be representative of the production component. The MPS shall reference all DPDs used in the production build.

For all AMSLs, destructive testing to assess the production component material properties shall be performed by using test specimens extracted/machined from prolongations or printed concurrently and co-located in the build with the component on the same build plate and subjected to the same thermal-post-production processing.

For AMSL 3, volumetric NDE shall be performed on the production component(s). As specified in 4.5.4.8.2, The additive manufacturer shall develop a NDE procedure and acceptance criteria. Acceptance criteria shall be in accordance with relevant design and material specifications as stated in the applicable material specification and/or API product specification.

8.2 Manufacturing Nonconformances

8.2.1 General

The additive manufacturer shall establish and maintain documented procedures to ensure that components that do not conform to specified requirements are prevented from unintended use or installation. These procedures shall provide for identification, documentation, evaluation, segregation (when applicable), and disposition of nonconforming components.

The additive manufacturer shall address nonconforming components in one or more of the following ways, in accordance with either API Specification Q1 or ISO 9001:

- repair or rework with subsequent inspection to meet specified requirements (correction);
- release under concession;
- scrap.

Repaired and/or reworked components shall be inspected in accordance with documented specifications of the additive manufacturer.

Where sampling is specified in Table 9 and Table 10, the following shall apply:

- When inspecting or testing production lots, a sample that fails to meet the applicable requirements shall result in rejection of the entire lot. The rejected lot shall be repaired or reworked with subsequent inspection to meet specified requirements (correction), released under concession, or scrapped.
- In the case of rework or concession, the entire lot shall be re-inspected for the failed characteristic(s) and any characteristic affected by rework.

When the nonconformance results from failure to meet purchaser requirements and/or specifications, the final disposition authority rests with the purchaser.

Records of nonconforming components, as well as actions resulting from the disposition of components, shall be maintained.

8.2.2 MEx Quality Control Requirements—Production Components

Quality control requirements for production component(s) manufactured by the MEx process shall be in accordance with Table 9.

Table 9—Quality Control Requirements for Mex—Production Components

Test Sample Configuration	Parameter[a] (Test Procedure)	AMSL 1	AMSL 2	AMSL 3
Specimens	Mechanical Properties[b] (4.5.4.4)	3 specimens in 1 orientation (3 in ZXY) (3 total)	3 specimens in 2 orientations (3 in the Z orientation and 3 90° form Z orientation) (6 total)	5 specimens in 2 orientations (5 in the Z orientation and 5 90° form Z orientation) (10 total)
	Specific Gravity (4.5.4.6)	3 specimens	3 specimens	3 specimens
	Porosity (4.5.4.7)	3 specimens	3 specimens	3 specimens
	Visual Inspection—Macro (4.5.4.8.1)	100 %	100 %	100 %
Component in the final condition[c]	Visual Inspection—Macro (4.5.4.8.1)	100 %	100 %	100 %
	Dimensional Inspection (4.5.4.90	Sampling	Sampling	100 %
	Performance Test (4.5.4.10)	___	___	1st and every 50th articles
	Specific Gravity (4.5.4.6)	___	___	1st and every 50th articles
	Porosity (4.5.4.7)	___	___	1st and every 50th articles
	NDE (4.5.4.8.3)	___	___	1st and every 50th articles

[a] Additional testing may be required by agreement depending on the component functionality. See Annex C.

[b] Test specimens prepared by the additive manufacturer in each of the orthogonal orientation notations according to ISO/ASTM 52921.

8.2.3 PBF Quality Control Requirements—Production Components

Quality control requirements for production component(s) manufactured by the PBF process shall be in accordance with Table 10.

Table 10—Quality Control Requirements for PBF—Production Component

Test Sample Configuration	Parameter[a] (Test Procedure)	AMSL 1	AMSL 2	AMSL 3
Specimens	Mechanical Properties[b] (4.5.4.4)	3 specimens in 1 orientation (3 in ZXY) (3 total)	3 specimens in 2 orientations (3 in the Z orientation and 3 90° form Z orientation) (6 total)	5 specimens in 2 orientations (5 in the Z orientation and 5 90° form Z orientation) (10 total)
	Specific Gravity (4.5.4.6)	3 specimens	3 specimens	3 specimens
	Porosity (4.5.4.7)	3 specimens	3 specimens	3 specimens
	Visual Inspection—Macro (4.5.4.8.1)	100 %	100 %	100 %
Component in the final condition[c]	Visual Inspection—Macro (4.5.4.8.1)	100 %	100 %	100 %
	Dimensional Inspection (4.5.4.90	Sampling	Sampling	100 %
	Performance Test (4.5.4.10)	___	___	1st and every 50th articles
	Specific Gravity (4.5.4.6)	___	___	1st and every 50th articles
	Porosity (4.5.4.7)	___	___	1st and every 50th articles
	NDE (4.5.4.8.3)	___	___	1st and every 50th articles

[a] Additional testing may be required by agreement depending on the component functionality. See Annex C.

[b] Test specimens prepared by the additive manufacturer in each of the orthogonal orientation notations according to ISO/ASTM 52921

9 Documentation

9.1 General

The additive manufacturer shall establish and maintain documented procedures to control all documents and data required by this standard.

Documents and data may be in any type of media (hard copy or electronic) and shall be:

- maintained to demonstrate conformance to specified requirements;
- legible;
- retained and readily retrievable;
- stored in an environment to prevent damage, deterioration, or loss;

— available and auditable by the purchaser.

9.2 Minimum Documentation and Retention

The documentation listed below shall be retained by the additive manufacturer for a minimum of 10 years following the date of manufacture:

— print location (site, room, building);
— build/batch number;
— printer model;
— printer firmware and software versions;
— MPS;
— Records of feedstock as defined in Section 4;
— DPD file as defined in Section 4;
— Thermal post-processing times, temperatures, and cooling media;
— Test records, including records of the examinations (NDE), mechanical testing, and material analysis, as described in Section 8.

NOTE Purchaser or regulatory requirements can specify a longer record retention period.

9.3 Documentation Provided with the Component(s)

At a minimum, the following documentation shall be supplied by the additive manufacturer for each component:

— certificate of conformance;
— MPS;
— printer model;
— printer firmware and software versions;
— test records, including records of the examinations (NDE), mechanical testing, and microscopic evaluations, as described in Section 8.

The purchaser can specify supplemental documentation requirements in accordance with Annex B.

10 Handling, Storage, and Shipping

Components shall be packaged for storage or transit in accordance with the additive manufacturer's written specifications.

Annex A

(informative)

Non-essential Additive Manufacturing Variables Guidance

A.1 Non-essential Additive Manufacturing Variables

Table A.1 defines non-essential AM variables. Changes to these do not require a requalification.

Table A.1 – Non-Essential Additive Manufacturing Variables

Parameter
Cleaning procedures for ancillary equipment (e.g. sieves, hand tools, power tools, powder storage containers, powder transport systems, and delivery mechanism to machine)
Method of CAD file transfer to machine
Machine room temperature, humidity
Facility cleanliness practices

Annex B

(informative)

Supplemental Documentation Requirements

The purchaser may select supplemental documentation from the list below at time of order placement:

- calibration records (purchaser to identify requirements for equipment when ordering);
- current quality management system certificate;
- print location (site, room, building);
- build/batch number;
- planned and unplanned print interruption records;
- records of feedstock as defined in Section 4;
- calibration records (purchaser to identify requirements for equipment when ordering);
- printing equipment maintenance records;
- current quality management system certificate;
- planned and unplanned print interruption records;
- NDE personnel qualification records;
- NDE procedures;
- operators training records.

Annex C

(informative)

Special Requirements

C.1 General

Additional testing may need to be conducted to verify that the component meets the requirements for a specific application (first article and quality test). The extra requirements, including the testing procedures, should be specified by agreement.

The following is a limited list of some additional requirements for AM components:

- surface finish and roughness;
- Rockwell hardness;
- electrical properties;
- dynamic mechanical analysis (DMA);
- heat deflection temperature (HDT);
- Izod impact;
- compression properties;
- shear properties;
- fatigue strength and fatigue limits;
- creep behavior;
- water absorption;
- flame classification/flammability.

C.2 Fluid Compatibility Test

The manufacturing process and conditions might affect the polymer microstructure, particularly in the case of semi-crystalline polymers (X_c factor). Therefore, the interaction between the additive manufactured polymer-based component and the fluid would vary depending on the microstructure. An engineering assessment is required to define the impact of the fluid on the component's performance.

A fluid compatibility test might be required to support the engineering assessment. ASTM D471, ASTM D543, ISO 23936, and NORSOK M710 are some of the reference protocols that estimate the effect of the fluid in the materials. Each protocol has a specific scope and reliability level; therefore, they should not be considered equivalent.

Bibliography

[1] ISO/ASTM 52901, *Additive Manufacturing — General principles — Requirements for purchased AM parts*

[2] ISO/ASTM 52910, *Additive manufacturing — Design — Requirements, guidelines and recommendations*