

Specification for Fabrication of Metal Components using Additive Manufacturing



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Specification for Fabrication of Metal Components using Additive Manufacturing

1st Edition

Prepared by the
AWS D20 Committee on Additive Manufacturing

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

This specification provides the general requirements for fabrication of metal components using additive manufacturing. It provides guidance for the interaction between the Engineer and the Contractor. It includes the design, qualification, fabrication, inspection, and acceptance of additively manufactured components. A commentary for the specification is included.



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Personnel

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Z. R. Tinkle	<i>Bechtel Plant Machinery</i>
J. B. West	<i>Sandia National Laboratory</i>

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Foreword

This foreword is not part of this standard but is included for informational purposes only.

The predecessors to additive manufacturing started in the early 1900's, but control systems that allowed its use for mainstream manufacturing have only become prevalent in recent years. This qualification and certification standard provides a structure for manufacturers and their customers to specify high quality components across many industries. Metal additive manufacturing (AM) systems first started as very small pieces of equipment using lasers and electron beams to make fine features using expensive to fabricate materials to produce difficult components. More recently, the equipment has become quite large with the capability to make large structures and has now incorporated the use of many arc welding processes and common structural materials. The growth in this segment of the welding industry has been fast due to its ability to make quick changes in designs and its ability to support just-in-time manufacturing methods.

The information contained in this standard was compiled by the American Welding Society's D20 Committee on Additive Manufacturing and has been carefully reviewed by a number of experts in the field. It must be noted that any operating parameters given in this standard will not be the only possible parameter combinations that can be employed for successfully processing the materials shown. Changes in material composition, dimensional tolerances, and machine calibration will cause changes in the resulting products. This is the first revision of the AWS D20.1/D20.1M standard.

Comments and suggestions for the improvement of this standard are welcome. They should be sent to the Secretary, AWS D20 Committee on Additive Manufacturing, American Welding Society, 8669 NW 36th St., # 130, Doral, FL 33166.

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Specification for Fabrication of Metal Components using Additive Manufacturing

1. General Requirements

1.1 Scope. This standard contains the requirements for fabricating metal components by use of additive manufacturing (AM) processes. Annex E provides flowcharts, for information, to assist the user of this standard in following the process for producing AM components in accordance with this document. When this standard is stipulated in contract documents, conformance with all provisions of the standard shall be required, except those provisions that the Engineer (see 1.5.1) or contract documents specifically modify or exempt. Additive manufacturing processes covered include those listed in Table 1.1, using either powder or wire feedstock, as applicable.

Table 1.1
Additive Manufacturing Processes

Process	Abbreviation
Laser Powder Bed Fusion	L-PBF
Electron Beam Powder Bed Fusion	EB-PBF
Laser Directed Energy Deposition	L-DED
Electron Beam Directed Energy Deposition	EB-DED
Plasma Arc Directed Energy Deposition	PA-DED
Gas Tungsten Arc Directed Energy Deposition	GTA-DED
Gas Metal Arc Directed Energy Deposition	GMA-DED

The following is a summary of the standard clauses:

Clause 1. **General Requirements:** Basic information on the scope and requirements of this standard.

Clause 2. **Normative References:** A listing of the documents that are required for the application of this standard.

Clause 3. **Terms and Definitions:** A list of technical terms and definitions required for the application of this standard.

Clause 4. **Design of Additively Manufactured Components:** Requirements for the design of additively manufactured components.

Clause 5. **Additive Manufacturing Machine and Procedure Qualification:** Qualification requirements for additive manufacturing machines and procedures.

Clause 6. **Additive Manufacturing Machine Operator Performance Qualification:** Qualification requirements for the operators of additive manufacturing machines.

Clause 7. **Fabrication:** Requirements for fabricating additively manufactured components.

Clause 8. **Inspection:** Requirements for the qualification of inspection personnel. Nondestructive and destructive examination requirements and acceptance criteria for qualification and production builds.

1.2 Units of Measure. This standard makes use of both the U.S. Customary Units and International System of Units (SI). The latter are shown within brackets ([]) or in appropriate columns in tables and figures. The measurements may not be exact equivalents; therefore, each system shall be used independently.

1.3 Safety. Safety and health issues and concerns are beyond the scope of this standard; some safety and health information is provided, but such issues are not fully addressed herein. Safety and health information is available from the following sources:

American Welding Society:

- (1) ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*
- (2) AWS Safety and Health Fact Sheets
- (3) Other safety and health information on the AWS website

Material or Equipment Manufacturers:

- (1) Safety Data Sheets supplied by materials manufacturers
- (2) Operating Manuals supplied by equipment manufacturers

Applicable Regulatory Agencies

Work performed in accordance with this standard may involve the use of materials that have been deemed hazardous, and may involve operations or equipment that may cause injury or death. This standard does not purport to address all safety and health risks that may be encountered. The user of this standard should establish an appropriate safety program to address such risks as well as to meet applicable regulatory requirements. ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes* should be considered when developing the safety program.

1.4 Classification. All components produced in accordance with this standard shall have their classification identified in the product definition data set and the Additive Manufacturing Procedure Specification (AMPS). Component classifications shall be as follows: Class A, Class B, or Class C. These classifications determine the level of qualification and inspection required and the acceptance criteria.

1.4.1 Determining Classifications. The Engineer shall determine the component classification considering material and process aspects that affect functional or systems requirements.

Class A—Critical application. A component, whose failure would cause significant danger to personnel, loss of control, loss of a system, loss of a major component, or an operating penalty.

Class B—Semi-critical application. A component whose failure would reduce the overall strength of the equipment or system or preclude the intended functioning or use of equipment, but loss of the system or the endangerment of personnel would not occur.

Class C—Noncritical application. A component whose failure would not affect the operation of the system or endanger personnel.

1.5 Responsibilities

1.5.1 Engineer's Responsibilities. The Engineer shall be responsible for the development of the contract documents that govern components produced under this standard. The Engineer may add to or otherwise modify the requirements of this standard to meet the particular requirements of a specific component. All requirements that modify this standard shall be incorporated into contract documents. The Engineer is responsible for evaluating the applicability and appropriate use of this standard.

The Engineer shall specify in contract documents, as necessary, and as applicable, the following:

- (1) Classification—Class A, B, or C (1.4.1)
- (2) Component and design requirements (4.1)
- (3) Essential process controls (4.1)
- (4) Feedstock specification requirements (4.2)

- (5) Material and component property data (4.2)
- (6) Design of witness specimens (4.3)
- (7) Product definition data set (4.4)
- (8) Tensile specimen removal plan for preproduction test builds (5.3)
- (9) Determination of acceptability of in-process correction (7.13)
- (10) Method of dimensional examination (8.2.2)
- (11) Approval of visual and dimensional examination plans (8.2.1 and 8.2.2)
- (12) Surface inspection in any condition other than fully machined (8.2.3 and 8.2.4)
- (13) Alternate method for examining builds that cannot be completely inspected by RT (8.2.5.2)
- (14) Sampling plan for Class B builds (8.2.5.2 and 8.3.3.1)
- (15) Location of tension test specimens within witness specimens (8.3.1.2)
- (16) Chemical analysis test method (8.3.3)
- (17) Acceptance criteria for tensile testing (8.4 and 8.4.3)
- (18) Disposition of components not meeting the requirements of Table 8.3 or Table 8.4 (8.4.2)
- (19) Acceptance criteria for metallographic testing (8.4.4)
- (20) Acceptance criteria for chemical analysis (8.4.5)
- (21) Acceptance criteria for density testing (8.4.6)
- (22) All Engineer's responsibilities listed in subsequent sections of this document
- (23) All additional requirements, identified by the Engineer, that are not specifically addressed in this standard.

1.5.2 Contractor's Responsibilities. The Contractor shall be responsible for performing work in conformance with the requirements of this standard and contract documents. The Contractor shall also be responsible for ensuring that any subcontracted work is performed in conformance with the requirements of this standard and all other contract documents. The Contractor shall also be responsible for supplying inspections in accordance with this standard and all other contract documents.

1.5.3 Inspector's Responsibilities. The Inspector shall be responsible for performing and documenting inspections in accordance with the requirements of this standard and all other contract documents.

1.5.4 Approval All references to the need for approval shall be interpreted to mean approval by the Engineer.

2. Normative References

The documents listed below are referenced within this publication and are mandatory to the extent specified herein. For undated references, the latest edition of the referenced standard shall apply. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply.

American Welding Society (AWS) documents:

AWS A5.01M/A5.01, *Welding Consumables—Procurement of Filler Metals and Fluxes*

AWS A3.0M/A3.0, *Standard Welding Terms and Definitions Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*

AWS A5.32M/A5.32, *Welding Consumables—Gases and Gas Mixtures for Fusion Welding and Allied Processes*

AWS B5.2, *Specification for the Training, Qualification, and Company Certification of Welding Inspector Specialists and Welding Inspector Assistants*

AWS QC1, *Specification for AWS Certification of Welding Inspectors*

ASTM International documents:

ASTM B215, *Standard Practices for Sampling Metal Powders*

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

ASTM E3, *Standard Guide for Preparation of Metallographic Specimens*

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

ASTM E407, *Standard Practice for Microetching Metals and Alloys*

ASTM E1417/E1417M, *Standard Practice for Liquid Penetrant Testing*

ASTM E1444/E144M, *Standard Practice for Magnetic Particle Testing*

ASTM E1570, *Standard Practice for Radiographic Examination*

ASTM E1742/E1742M, *Standard Practice for Radiographic Examination*

ASTM E2651, *Standard Guide for Powder Particle Size Analysis*

International Organization for Standardization (ISO) documents:

ISO/ASTM 52900, *Standard Terminology for Additive Manufacturing—General Principles—Terminology*

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

American Society of Mechanical Engineers (ASME) documents:

ASME Y14.41, *Digital Product Definition Data Practices*

ASME Y14.5M, *Dimensioning and Tolerancing*

ASME Y14.46, *Product Definition for Additive Manufacturing*

3. Terms and Definitions

AWS A3.0M/A3.0, *Standard Welding Terms and Definitions*, provides the basis for terms and definitions used herein. In addition, terms used in this standard shall be interpreted in conformance with the definitions given in the latest edition of:

- ISO/ASTM 52900, *Standard Terminology for Additive Manufacturing—General Principles—Terminology*
- ISO/ASTM 52921, *Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies*
- ASME Y14.41, *Digital Product Definition Data Practices*

However, the following terms and definitions are included to accommodate usage specific to this document.

Additive Manufacturing Procedure Specification (AMPS). A document stating all operating variables to provide requirements for production of a component using an additive manufacturing process.

build model. The model that contains the design part geometry and orientation for the entire build volume, including support structure, machining stock, and witness specimens.

Contractor. A company or individual representing a company, responsible for fabrication or manufacturing in accordance with this standard.

Engineer. The duly designated individual acting for, and on behalf of, the Owner on all matters within the scope of this standard.

Inspector. The duly designated individual acting for, and on behalf of, the Contractor on all inspection and quality matters within the scope of this standard and applicable contract documents.

Machine Qualification Record (MQR). A record of the variables used to produce an acceptable standard qualification build and corresponding results of tests conducted to support qualification of an additive manufacturing machine.

Owner. The individual, company, or government agency having legal title or right to the product produced in accordance with this standard.

preproduction test build. A qualification test build fabricated using the same fabrication-specific portions of the product definition data set for the entire build envelope and the same AM procedure as production components. This build supports qualification of an AM procedure.

Procedure Qualification Record (PQR). A record of the variables used for production of an acceptable preproduction test build and corresponding results of tests conducted to support qualification of an Additive Manufacturing Procedure Specification (AMPS).

product definition data set. All information required by the Engineer to produce an AM component in accordance with this standard. See 4.4.

standard qualification build. A qualification build from which standard test specimens are removed, tested, and evaluated. This build supports qualification of an AM machine.

Subcontractor. A person or company having a contract (as an “independent contractor” and not an employee) with a Contractor to provide some portion of the work or services on a project, for which the Contractor is responsible.

support structure. Material deposited during the AM build cycle used to support the integrity of the build but not considered part of the final part geometry. Support structures may include mechanical supports, thermal supports, or protective features.

Qualifier. The Employer, organization, or individual responsible for conducting and supervising performance qualification testing.

witness specimen. Material built along with a preproduction test build or production build for reference or testing purposes, from which test specimens can be obtained.

4. Design Requirements for Additively Manufactured Components

4.1 Scope. This clause covers the requirements for the design of additively manufactured components. The Engineer shall design and define the component requirements to ensure compliance with all functional and system requirements.

Further, the Engineer shall define additional essential process controls, as necessary, and shall substantiate that all design requirements can be met by components produced in accordance with the qualification, fabrication, and inspection requirements specified in this document or as modified by the Engineer, if modifications to this standard are specified in Contract documents.

4.2 Material Requirements. The Engineer shall provide the feedstock specification requirements and develop or obtain appropriate material property requirements to satisfy the component design. These material property requirements shall apply to the final state of the component following all post-processing steps required for that component [e.g., stress relief, machining, hot isostatic pressing (HIP)]. These material property requirements shall include, at a minimum, those needed to provide acceptance criteria for the testing requirements of Table 5.1.

4.3 Witness Specimens for Powder Bed Fusion. Witness specimens shall be included in the build model for Class A and Class B PBF components.

4.3.1 Class A Witness Specimens. For Class A components, a minimum of four (4) witness specimens shall be distributed throughout the build model. Three of the witness specimens are to be tested in accordance with Clause 8 (8.3.1.2, 8.3.3.1). The remaining witness specimen is to be reserved in the event that it is needed to evaluate the acceptability of an in-process correction (7.13). The Engineer shall design the witness specimens within the following requirements:

(1) The height of each witness specimen shall be at least the maximum height of the component build (in the z direction).

(2) The geometry of each witness specimen shall be such that the test specimens required by Clause 8 (8.3.1.2, 8.3.3.1) can be removed from the witness specimen. The witness specimens, and the test specimens removed from the witness specimens, may be in any orientation relative to the build platform.

4.3.2 Class B Witness Specimens. For Class B components, a minimum of two (2) witness specimens shall be included in the build model. One of the witness specimens is to be tested in accordance with Clause 8 (8.3.1.2, 8.3.3.1). The remaining witness specimen is to be reserved in the event that it is needed to evaluate the acceptability of an in-process correction (7.13). The witness specimens shall meet the requirements of 4.3.1(1) and 4.3.1(2).

4.4 Product Definition Data Set Requirements. The product definition data set shall contain all information specified by the Engineer to produce the AM component in accordance with the requirements of this standard. At a minimum, the product definition data set shall contain the following:

- (1) Component classification level (Class A, B, or C) as defined in 1.4.
- (2) Drawing or model of final required component dimensions, including surface finish requirements.
- (3) Component material type and property value requirements.
- (4) Allowable AM process(es), from Table 1.1.
- (5) Component post-processing requirements. This includes, but is not limited to, surface treatment method(s), surface finishing method(s), and thermal processing method(s).
- (6) Inspection requirements. Clause 8 provides the default inspection methods and acceptance criteria. Additional and alternate inspection requirements defined by the Engineer shall be included in the product definition data set.

5. Additive Manufacturing Machine and Procedure Qualification

5.1 General. The purpose of an AM machine qualification is to demonstrate that an AM machine is capable of producing specimens that meet required properties throughout the build envelope within which components are to be fabricated using a qualified AM procedure. The purpose of an AM procedure qualification is to demonstrate the capabilities of an AM procedure to produce a specific component that meets required properties.

5.1.1 Machine Qualification Record (MQR) and Procedure Qualification Record (PQR). The MQR and PQR shall address all qualification variables (see 5.4) applicable to the AM process used for the qualification builds. Additionally, the MQR and PQR shall contain all other items identified in the qualification record templates provided in Annex A for the AM process used. The MQR and PQR shall also include a certifying statement acknowledging the validity of the data and certifying that the qualification test specimens were prepared, fabricated, and tested in accordance with this standard. There is no required format for the MQR or PQR; any format may be used provided that all applicable information is recorded.

5.1.2 MQR and PQR Revisions. MQRs and PQRs shall not be revised except to correct errors or add new or omitted information. All such changes shall be identified, authorized by the Contractor, and dated on the MQR or PQR.

5.1.3 AMPS. The AMPS shall include the AM process, the component classification, the build model file name, and all build platform, feedstock, machine, environment, build parameters, and post-processing information identified in the Annex A qualification record templates for the applicable process. The AMPS shall reference all MQRs and PQRs used to qualify the AMPS. There is no required format for the AMPS; any format may be used provided that all applicable information is recorded.

5.1.4 Traceability of MQRs and PQRs. AMPSs, MQRs, and PQRs shall be identified according to a system that allows permanent traceability from the AMPS to its supporting MQR(s) and PQR(s).

5.1.5 Changes within an AMPS. A change in an AMPS beyond that allowed in 5.4 shall require requalification of the AM procedure and/or AM machine (as applicable per 5.4) and preparation of a new PQR and/or MQR, and AMPS. Changes not addressed in 5.4 shall not require machine or procedure requalification, but shall be documented in a new or revised AMPS. If a build parameter file provided by the AM machine manufacturer is used for procedure qualification builds and the exact parameter values contained in the file are not known by the Contractor, then the Contractor shall have a means in place for ensuring that the same build parameter file is used for the production builds. If the parameters or machine settings used by that build parameter file change, then requalification is required unless the Contractor documents that these changes are within the qualified limits of 5.4.

5.1.6 Transferring an AMPS. An AMPS qualified by one Contractor is not transferrable to another Contractor.

5.1.7 In-Process Monitoring. In-process monitoring methods that do not alter or control any qualification variable identified in 5.4 are not required to be documented as part of the AMPS.

The use of any in-process monitoring method(s) that alters or controls any qualification variable identified in 5.4 shall be documented in the MQR, PQR, and AMPS. This documentation shall include the type of monitoring, the monitoring system settings used, and the qualification variables listed in 5.4 affected by monitoring. If an in-process monitoring method alters or controls any qualification variable, the in-process monitoring equipment and software shall be considered to be a major equipment subcomponent (5.4.3 or 5.4.10).

5.2 Qualification Test Builds. Machine qualification is required for Class A and Class B components and requires the fabrication and testing of a standard qualification build (5.2.1, 5.2.2). Machine qualification is not required for Class C components.

Procedure qualification is required for Class A, B, and C components and requires the fabrication and testing of a preproduction test build (5.2.3).

The testing requirements for standard qualification builds and preproduction test builds are shown in Table 5.1.

5.2.1 Powder Bed Fusion Standard Qualification Build for Machine Qualification. AM machine qualification for Class A and Class B PBF components shall utilize a standard qualification build(s) that meets the requirements of 5.2.1.1 through 5.2.1.5.

5.2.1.1 Standard Qualification Build Design. The standard qualification build shall provide tension test specimens from each corner (or at four, equally-spaced extremes at the edges of the build platform) and the center of the build volume being qualified. Half of the standard qualification build tension test specimens in each location shall represent a thin feature (maximum of 0.04 in [1 mm]). The other half of the standard qualification build tension specimens in each location shall represent a thick feature (minimum of 0.25 in [6.25 mm]). Examples of standard qualification build designs are shown in Annex C.

Table 5.1
Inspection and Testing Requirements for Machine and Procedure Qualification

Test Method		Powder Bed Fusion			Directed Energy Deposition		
		Class A	Class B	Class C	Class A	Class B	Class C
Machine Qualification Standard Qualification Build(s)	Visual Examination	Yes	Yes	—	Yes	Yes	—
	Dimensional Inspection	Yes	Yes	—	Yes	Yes	—
	Radiographic Examination	Yes	Yes	—	Yes	Yes	—
	Density Testing	Yes	Yes	—	Yes	Yes	—
	Tension Tests	54	54	—	36	36	—
	Metallographic Examination	Yes	Yes	—	Yes	Yes	—
Procedure Qualification Preproduction Test Build(s)	Visual Examination	Yes	Yes	Yes	Yes	Yes	Yes
	Dimensional Inspection	Yes	Yes	Yes	Yes	Yes	Yes
	Penetrant Testing	Yes	Yes	—	Yes	Yes	—
	Radiographic Examination	Yes	Yes	—	Yes	Yes	—
	Density Testing	Yes	Yes	Yes	Yes	Yes	Yes
	Tension Tests (Witness Specimens)	3	1	—	—	—	—
	Tension Tests (Component)	3	3	—	3	3	—
	Metallographic Examination	Yes	Yes	Yes	Yes	Yes	Yes
	Chemical Analysis	Yes	Yes	—	Yes	Yes	—

Additionally, dimensional inspection features shall be included as part of the standard qualification build. Material shall be built at each corner of the build platform (or at four, equally-spaced extremes at the edges of the build platform) that represents the smallest resolution feature(s) of components to be fabricated to an AMPS utilizing the AM machine to be qualified with this build.

5.2.1.2 Number and Orientation of Test Specimens. The tension test specimens in each standard qualification build shall include the following orientations: the tensile axis within the X-Y plane, the tensile axis along the Z axis, and the tensile axis at 45° ($\pm 15^\circ$) from the Z axis.

For Class A and Class B components, 54 tension test specimens are required, at a minimum. These 54 specimens shall be comprised of tension test specimens from each of the eight corners (or at four, equally-spaced extremes at the edges of the build platform and four at the top of the build volume) and in the center of the build volume to be qualified. Each corner and the center of the build volume shall contain a minimum of one thick specimen and one thin specimen for each of the three orientations identified above. All tension test specimens in the corners shall be built such that the geometric center of any test specimen is no further than 3 in [75 mm] from the identified corner of the qualified build volume. For non rectangular or non square build platforms, these specimens shall be built such that the geometric center of any test specimen is no further than 3 in [75 mm] from the extreme of the qualified build volume.

The qualified build volume is represented by the bounding volume of the gage region of all tension test specimens (i.e., the smallest volume that encompasses all gage regions). If the machine build volume cannot support the required test specimens due to space restrictions, the Contractor shall submit a modified machine qualification build plan to the Engineer for approval.

5.2.1.3 Specimen Size. The tension test specimens shall be prepared in accordance with standard or subsize specimen dimensions as given in ASTM E8/E8M, *Standard Test Methods for Tension Testing of Metallic Materials*. The dimensions of the grip regions of the tension test specimens may be altered from those given in ASTM E8/E8M as agreed upon by the Engineer and Contractor.

5.2.1.4 Specimen Condition. All post-processing, except for machining and surface finishing, including the order in which post-processing operations are performed, shall be the same for the machine qualification build as will be used for the applicable production component(s). All post-processing parameters used shall be recorded as part of the MQR.

5.2.1.5 Metallographic Specimens. Metallographic specimens shall be examined to meet the requirements of 8.3.2.1.

5.2.2 Directed Energy Deposition Standard Qualification Build for Machine Qualification. DED machine qualification for Class A and Class B shall utilize a standard qualification build(s) from which test specimens can be machined in accordance with 5.2.2.1 through 5.2.2.5. If the geometry of the preproduction test build (5.2.3) allows the removal of tension test specimens meeting the requirements of 5.2.2.2 and 5.2.2.3, the preproduction test build may be used in lieu of a separate standard qualification build.

5.2.2.1 Standard Qualification Build Design. The standard qualification build shall provide material for testing from build conditions (features) that are built both parallel to the build surface and normal to the build surface, as described below. The standard qualification build shall also provide features for ensuring that the AM machine is building material with acceptable dimensional accuracy throughout the build platform.

The standard qualification build(s) shall provide material representing the conditions that will be present in the AM component. An example of standard qualification build features is shown in Figure 5.1. At a minimum, the following conditions are required to be represented by the standard qualification build:

(1) Vertical Plane Condition—This condition is defined as any portion of a DED build that is less than three deposition passes wide, is five or more deposition layers thick, and extends for a length greater than 10 times the width of a single DED pass.

(2) Horizontal Plane Condition—This condition is defined as any portion of a DED build that is fabricated directly upon the build platform that is less than three deposition layers thick, is five or more deposition passes wide, and extends for a length greater than 10 times the width of a single deposition pass.

(3) Dimensional Inspection Features—Material shall be built at each corner of the build platform (or at four, equally-spaced extremes at the edges of the build platform) that represents the smallest resolution feature(s) of components to be fabricated to an AMPS utilizing the AM machine to be qualified with this build.

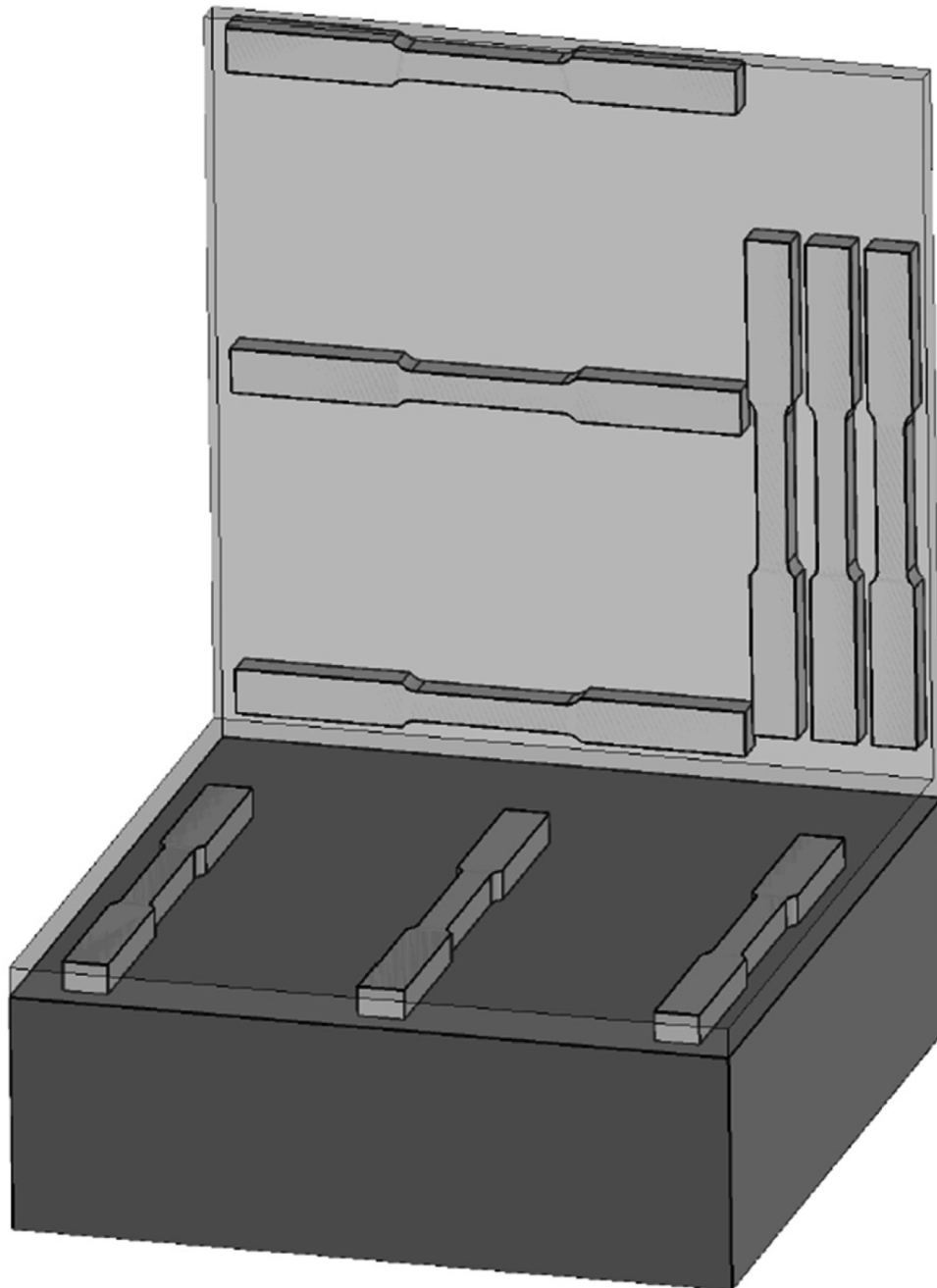


Figure 5.1—Example of Specimen Arrangement in Vertical and Horizontal Plane Conditions for a Directed Energy Deposition Standard Qualification Build

Image courtesy of Brett Preston, Los Alamos National Laboratory

5.2.2.2 Number and Orientation of Test Specimens. For conditions (1) and (2) described in 5.2.2.1, tension test specimens shall be machined as follows:

(1) Vertical Plane Condition

- Three test specimens with their tensile axis parallel to the build platform surface and aligned longitudinally with the primary deposition direction, evenly spaced along the Z-axis
- Three test specimens with their tensile axis perpendicular to the build platform surface (i.e., parallel to the Z-axis)

(2) Horizontal Plane Condition

- Three test specimens with their tensile axis parallel to the build platform surface and aligned perpendicular to the primary deposition direction

5.2.2.3 Specimen Size. The tension test specimens shall be prepared in accordance with standard or subsize specimen dimensions as given in ASTM E8/E8M, *Standard Test Methods for Tension Testing of Metallic Materials*. The dimensions of the grip regions of the tension test specimens may be altered from those given in ASTM E8/E8M as agreed upon by the Engineer and Contractor.

5.2.2.4 Specimen Condition. All post-processing, except for machining and surface finishing, including the order in which post-processing operations are performed, shall be the same for the machine qualification build as will be used for the applicable production component(s). All post-processing parameters used shall be recorded as part of the MQR.

5.2.3 Preproduction Test Build for Procedure Qualification. The preproduction test build for PBF and DED procedure qualifications shall consist of a test build fabricated using the same product definition data set for the entire build envelope and using the same AM procedure as the production component(s).

5.2.3.1 Powder Bed Fusion Witness Specimens. Witness specimens shall be built with Class A and Class B PBF preproduction test builds, as detailed in 4.3.

5.2.3.2 DED Components with Integrated Build Platform. When qualifying DED procedures for production DED builds that will not be removed from the build platform, such as in the case of using DED for repair of a component, three additional tension test specimens shall be extracted from a preproduction test build and tested for each integrated build platform material. These tension test specimens shall consist of materials representative of the component. For example, if the component consists of a DED build on a forging, then the test specimens shall be taken from a DED build on forged material. The tension test specimens shall contain the interface between the build platform and the DED build within the gage region. The tension test specimens may be in any orientation relative to the build platform. The integrated build platform tension test specimens may be extracted from the preproduction test build if sufficient material is available.

5.3 Examination and Testing Requirements for Qualification Builds. Qualification builds shall be inspected and tested as required by Table 5.1 in accordance with the requirements of Clause 8 and for conformance to the acceptance criteria identified in Clause 8. Tensile specimens shall be removed from the preproduction test build from component locations specified by the Engineer.

5.4 Qualification Variables. Items in Table 5.2 and Table 5.3 that are marked as “M” require requalification of only the AM machine. Items in Table 5.2 and Table 5.3 that are marked as “P” require requalification of only the AM procedure for all classes of components. Items in Table 5.2 and Table 5.3 that are marked as “Q” require requalification of both the AM machine and the AM procedure.

5.5 Additive Manufacturing Procedure Specification Acceptance An AMPS is qualified when the required AM machine and procedure qualifications have been successfully completed and the AMPS contains all items required by Clause 5.

Table 5.2
Qualification Variables for Powder Bed Fusion Processes

Qualification Variables for Powder Bed Fusion	PBF L	PBF EB
5.4.1 Build Design		
(1) <u>Build model.</u> Any change to the build model.	P	P
(2) <u>Component classification.</u> Any increase in component classification (i.e., from Class C to Class B or Class A, or from Class B to Class A).	Q	Q
5.4.2 Material		
(1) <u>Feedstock specification and classification.</u> Any change in feedstock specification or classification (e.g. group, type, or class), form, or feedstock manufacturing process.	Q	Q
(2) <u>Powder composition.</u> (sampling per 7.4.2.3) Any change beyond the specified tolerances established by the Engineer and Contractor for the powder specification in terms of chemical composition.	Q	Q
(3) <u>Particle size distribution.</u> (sampling per 7.4.2.3) Any change beyond the specified tolerances established by the Engineer and Contractor for the powder specification in terms of particle size distribution.	Q	Q
(4) <u>Rheological performance.</u> (sampling per 7.4.2.3) Any change beyond the specified tolerances established by the Engineer and Contractor for the powder specification in terms of rheological performance.	Q	Q
(5) <u>Build platform material specification and classification.</u> Any change in build platform material specification or classification (e.g. group, type, and/or class) or form.	P	P
(6) <u>Build platform thickness.</u> A change in build platform thickness by $\pm 10\%$.	P	P
5.4.3 Machine		
(1) <u>Machine location.</u> Any physical move of machine location.	M	M
(2) <u>Machine manufacturer and model.</u> Any change to machine manufacturer or model.	Q	Q
(3) <u>Machine software version.</u> Any change to machine software version.	Q	Q
(4) <u>Machine serial number.</u> A change from the machine documented on the MQR to any other machine.	Q	Q
(5) <u>Major equipment subcomponents.</u> A change in major equipment subcomponents, such as PC hardware, power delivery, automation system, or material delivery.	M	M
(6) <u>Recoater.</u> Any change to the recoater type or material.	Q	Q
5.4.4 Environment		
(1) <u>Build platform preheat temperature.</u> Any change to the specified build platform preheat temperature.	Q	Q
(2) <u>Shielding gas composition.</u> A change in the specified nominal composition of shielding gas.	Q	—
(3) <u>Shielding gas flow rate.</u> Any change in the flow rate greater than $\pm 10\%$.	Q	—

(continued)

Table 5.2 (continued)
Qualification Variables for Powder Bed Fusion Processes

Qualification Variables for Powder Bed Fusion	PBF L	PBF EB
(4) <u>Supplemental gas shielding.</u> The addition or deletion of supplemental gas shielding.	Q	—
(5) <u>Build chamber supply gas composition.</u> A change in the specified nominal build chamber gas supply composition.	Q	—
(6) <u>Vacuum pressure.</u> A change in programmed vacuum pressure.	—	Q
(7) <u>Environmental enclosure.</u> A change to environmental enclosure hardware or configuration.	Q	Q
5.4.5 Heat Source Characteristics		
(1) <u>Heat input.</u> Any programmed change to a parameter that affects heat input.	P	P
(2) <u>Pulse characteristics.</u> Any change in pulse frequency or waveform.	Q	Q
(3) <u>Pulsing.</u> Introduction or withdrawal of pulsing or waveform control.	Q	Q
(4) <u>Preheating by beam splitting.</u> Any change in beam splitting parameters.	Q	Q
(6) <u>Focus settings.</u> Any change in programmed focus settings.	Q	Q
5.4.6 Deposition Characteristics		
(1) <u>Travel speed.</u> Any change in programmed travel speed.	P	P
(2) <u>Scan strategy.</u> Any change in scan strategy.	P	P
(3) <u>Hatch overlap.</u> A change in the distance between centers of parallel hatches.	P	P
(4) <u>Hatch spacing.</u> A change in the distance between centers of adjacent scan vectors.	P	P
(5) <u>Specific settings affecting edge and surface build conditions.</u> Any change to the settings used to alter the build at edges or surfaces.	P	P
(6) <u>Programmed layer height.</u> Any change in programmed layer height.	Q	Q
5.4.7 Post-build Heat Treatment / Processing		
(1) <u>Post-build cooldown procedure.</u> Any change to the post-build cooldown procedure that affects the cooling rate.	P	P
(2) <u>Post-build heat treatment.</u> Any change to nominal post-build heat treatment time and temperature values.	Q	Q
(3) <u>Hot isostatic press (HIP).</u> The addition or deletion of HIP, or any change to nominal HIP temperature, pressure, and time values.	Q	Q
(4) <u>Surface treatment.</u> The addition of or change to any post-build surface treatment (e.g., peening).	P	P
(5) <u>Surface finishing.</u> The elimination of or change to surface finishing method (e.g., machining, grinding).	P	P

Table 5.3
Qualification Variables for Directed Energy Deposition Processes

Qualification Variables for Directed Energy Deposition	DED L (powder)	DED L (wire)	DED EB	DED PA (powder)	DED PA (wire)	DED GTA	DED GMA
5.4.8 Build Design							
(1) <u>Build model.</u> Any change to the build model.	P	P	P	P	P	P	P
(2) <u>Component classification.</u> Any increase in component classification (i.e., from Class C to Class B or Class A, or from Class B to Class A).	Q	Q	Q	Q	Q	Q	Q
5.4.9 Material							
(1) <u>Feedstock specification and classification.</u> Any change in feedstock specification and classification (e.g. group, type, and/or class), form, or feedstock manufacturing process.	Q	Q	Q	Q	Q	Q	Q
(2) <u>Powder composition.</u> (sampling per 7.4.2.3) Any change beyond the specified tolerances established by the Engineer and Contractor for the powder specification in terms of chemical composition.	Q	—	—	Q	—	—	—
(3) <u>Particle size distribution.</u> (sampling per 7.4.2.3) Any change beyond the specified tolerances established by the Engineer and Contractor for the powder specification in terms of particle size distribution.	Q	—	—	Q	—	—	—
(4) <u>Rheological performance.</u> (sampling per 7.4.2.3) Any change beyond the specified tolerances established by the Engineer and Contractor for the powder specification in terms of rheological performance.	Q	—	—	Q	—	—	—
(5) <u>Wire diameter.</u> Any change in the specified wire diameter by $\pm 5\%$.	—	Q	Q	—	Q	Q	Q
(6) <u>Build platform material specification and classification.</u> Any change in build platform material specification or classification (e.g. group, type, and/or class) or form.	P	P	P	P	P	P	P
(7) <u>Build platform thickness.</u> A change in build platform thickness by $\pm 10\%$.	P	P	P	P	P	P	P
(8) <u>Powder feed rate.</u> Any change in measured powder mass flow rate by $\pm 5\%$.	Q	—	—	Q	—	—	—
(9) <u>Wire feed rate.</u> Any change in programmed wire feed rate by $\pm 5\%$.	—	Q	Q	—	Q	Q	Q
5.4.10 Machine							
(1) <u>Machine location.</u> Any physical move of machine location.	Q	Q	Q	P	P	P	P
(2) <u>Machine manufacturer and model.</u> Any change to machine manufacturer or model.	M	M	M	M	M	M	M
(3) <u>Machine software version.</u> Any change to machine software version that affects any qualification variable listed in Table 5.3.	M	M	M	M	M	M	M

(continued)

Table 5.3 (continued)
Qualification Variables for Directed Energy Deposition Processes

Qualification Variables for Directed Energy Deposition	DED L (powder)	DED L (wire)	DED EB	DED PA (powder)	DED PA (wire)	DED GTA	DED GMA
(4) <u>Machine serial number.</u> A change from the machine documented on the MQR to any other machine.	Q	Q	Q	M	M	M	M
(5) <u>Major equipment subcomponents.</u> A change in major equipment subcomponents, such as PC hardware, power delivery, automation system, or material delivery.	M	M	M	M	M	M	M
5.4.11 Environment							
(1) <u>Build platform preheat temperature.</u> Any change to the specified build platform preheat temperature.	P	P	P	P	P	P	P
(2) <u>Interpass temperature.</u> Any programmed change that would result in a deviation in maximum interpass temperature.	P	P	P	P	P	P	P
(3) <u>Shielding gas composition.</u> A change in the specified nominal composition of shielding gas.	Q	Q	—	Q	Q	Q	Q
(4) <u>Powder carrier gas flow rate.</u> Any change in the flow rate of $\pm 10\%$ or greater.	Q	—	—	Q	—	—	—
(5) <u>Shielding gas flow rate.</u> Any change in the flow rate greater than $\pm 10\%$.	Q	P	—	Q	P	P	P
(6) <u>Supplemental gas shielding.</u> The addition or deletion of supplemental gas shielding.	Q	P	—	Q	P	P	P
(7) <u>Supply gas composition.</u> A change in the specified nominal gas supply composition, either for a build chamber or to a supply nozzle.	Q	Q	—	Q	Q	Q	Q
(8) <u>Vacuum pressure.</u> An increase in vacuum pressure by more than an order of magnitude (torr) of a vacuum.	—	—	Q	—	—	—	—
(9) <u>Environmental enclosure.</u> A change to environmental enclosure hardware and configuration.	M	M	M	M	M	M	M
(10) <u>Interpass cleaning.</u> Any change to interpass cleaning methods.	—	P	—	P	P	P	P
5.4.12 Heat Source Characteristics							
(1) <u>Heat input.</u> Any programmed change to a parameter that affects heat input.	Q	P	P	P	P	P	P
(2) <u>Pulse characteristics.</u> Any change in pulse frequency or waveform.	Q	Q	Q	Q	Q	Q	Q
(3) <u>Pulsing.</u> Introduction or withdrawal of pulsing or waveform control.	Q	Q	Q	Q	Q	Q	Q
(4) <u>Preheating by beam splitting.</u> Any change in beam splitting parameters.	Q	P	P	—	—	—	—
(5) <u>Use of energized (“hot”) wire.</u> A change from using energized wire to un-energized wire, or vice versa.	—	Q	Q	—	Q	Q	Q
(6) <u>Focus settings.</u> Any change in programmed focus settings.	Q	P	P	—	—	—	—

(continued)

Table 5.3 (continued)
Qualification Variables for Directed Energy Deposition Processes

Qualification Variables for Directed Energy Deposition	DED L (powder)	DED L (wire)	DED EB	DED PA (powder)	DED PA (wire)	DED GTA	DED GMA
5.4.13 Deposition Characteristics							
(1) <u>Travel speed.</u> Any change in programmed travel speed	P	P	P	P	P	P	P
(2) <u>Scan strategy.</u> Any change in scan strategy	P	P	P	P	P	P	P
(3) <u>Hatch overlap.</u> A change in the distance between centers of parallel hatches.	P	—	—	—	—	—	—
(4) <u>Hatch spacing.</u> A change in the distance between centers of adjacent scan vectors.	P	—	—	—	—	—	—
(5) <u>Starting working distance.</u>	Q	Q	Q	—	—	—	—
(6) <u>Specific settings affecting edge and surface build conditions.</u> Any change to the settings used to alter the build at edges and/or surfaces.	P	P	P	P	P	P	P
(7) <u>Programmed layer height.</u> Any change in programmed layer height.	Q	—	—	—	—	—	—
(8) <u>Wire delivery parameters.</u> Any change in incidence angle, offset distance from centerline of heat source, or path orientation.	—	P	P	—	P	P	P
5.4.14 Post-build Heat Treatment / Processing							
(1) <u>Post-build cooldown procedure.</u> Any change to the post-build cooldown procedure that affects the cooling rate.	P	P	P	P	P	P	P
(2) <u>Post-build heat treatment.</u> Any change to nominal post-build heat treatment time and temperature values.	Q	Q	Q	Q	Q	Q	Q
(3) <u>Hot isostatic press (HIP).</u> The addition or deletion of HIP, or any change to nominal HIP temperature, pressure, and time values.	Q	Q	Q	Q	Q	Q	Q
(4) <u>Surface treatment.</u> The addition of or change to any post-build surface treatment (e.g., peening).	P	P	P	P	P	P	P
(5) <u>Surface finishing.</u> The elimination of or change to surface finishing method (e.g., machining, grinding).	P	P	P	P	P	P	P

6. Additive Manufacturing Machine Operator Performance Qualification

6.1 General. The purpose of the AM machine operator qualification is to determine the ability of AM machine operators to complete acceptable AM component builds using a given AM machine. This clause establishes the minimum requirements for AM machine operator performance qualification.

6.1.1. AM machine operator performance qualification shall be performed for a specific AM machine manufacturer and model number. Completion of AM machine operator qualification will qualify the AM machine operator for that specific AM machine model. The AM machine operator shall complete a full qualification to become qualified for any other model of AM machine, regardless of the AM process or machine manufacturer. Changes to any machine software versions shall require completion of the partial requalification requirements identified in 6.3.5.

6.1.2. The AM machine operator undertaking performance qualification tests shall be under the full supervision and control of a Qualifier during written examinations and the fabrication of test pieces. At the option of the Contractor, an outside organization may be engaged to perform the duties of the Qualifier. The Contractor shall be responsible for evaluating the outside organization to ensure that services are in accordance with the Qualification Program (6.3.1).

6.2 Levels of Qualification. There are three levels of AM machine operator: Class A, Class B, and Class C. These levels correspond to the three component classifications identified in 1.4.1. An AM machine operator who is qualified to a Class A level is also qualified to produce Class B and Class C components. An AM machine operator who is qualified to a Class B level is also qualified to produce Class C components. An AM machine operator who is qualified to a Class C level is only qualified to produce Class C components.

6.3 Qualification Requirements. Qualification of an AM machine operator shall be based on the following items:

- (1) Training, including successful completion of written examinations
- (2) Practical examinations
- (3) Demonstration build

6.3.1 Qualification Program. Training and examinations shall be administered by the Qualifier in accordance with a formal, documented program. The AM machine operator qualification program shall include:

- (1) A written procedure identifying all aspects of training and examinations, including requirements for passing examinations and allowances for re-examination
- (2) Written examination questions and answer keys
- (3) Practical examination requirements and answer keys
- (4) Means of maintaining training, examination, demonstration build, and inspection records
- (5) Re-testing requirements for AM machine operators

6.3.2 Training. Personnel undergoing qualification shall complete organized training to become familiar with the principles of the AM process and the operation of the AM machine. Training may be provided by a qualified AM machine operator for a given AM machine, or by an outside organization that provides training on the AM machine.

6.3.2.1 Training and Examination Topics. Training and examination topics shall include the following, as a minimum, as applicable to the AM process and machine for which the operator is qualifying:

- (1) Feedstock material storage (e.g., use of proper storage containers to protect materials from degradation)
- (2) Feedstock material safety (e.g., reactive powder handling)
- (3) Feedstock material setup (e.g., sieving powder, loading powder, feeding wire)
- (4) Equipment and component cleaning requirements (e.g., build platform cleanliness, removal of powder from a build chamber and component)
- (5) Performance of machine calibrations that are done by operations personnel
- (6) Common build defects (e.g., porosity, incomplete fusion), their causes, and precautions for prevention
- (7) Environmental controls (e.g., shielding gas requirements, build chamber environment restrictions)

(8) Loading of qualified build parameters (a preprogrammed set of build parameters or Contractor-developed build parameters, ensuring the appropriate software version is in use)

(9) AM machine preventative maintenance

(10) Running and monitoring AM build cycles (e.g., monitoring recoater for damage, monitoring environmental readings, visual checks to ensure build is proceeding as expected)

(11) Recording AM build cycle data

(12) Recovery from planned (e.g., feedstock reloading) and unplanned (e.g., recoater contacts components) build cycle interruptions

(13) Removing completed components and build platform from AM machine

(14) Equipment and subcomponent safety

6.3.2.2 Training Hours. AM machine operators are required to undergo a minimum of 40 hours of training specific to the use of the AM machine (manufacturer and model number) for which they are qualifying. However, the hours of training for personnel who perform only limited portions of AM machine operation (see commentary C-6.3.2.2) may be less than that specified, provided the time and type of training is documented and any limitation or restriction on the qualification is described in the certification records.

An AM machine operator's previous training may be accepted by the Contractor if documented and verified. The documentation shall be included as part of the qualification records (6.6).

6.3.3 Practical Examination. Qualification of an AM machine operator requires that the operator complete a practical examination that consists of demonstrating an understanding of all applicable topics in 6.3.2.1. The practical examination shall be administered by the Qualifier in accordance with the Qualification Program (6.3.1). The practical examination shall be performed using the same AM machine model and software version for which the operator is qualifying.

For personnel who perform only limited portions of AM machine operation, only the portions of AM machine operation for which the operator is intending to qualify need to be demonstrated during the practical examination. Any limitation or restriction on the qualification shall be described in the qualification records (6.6).

6.3.4 Demonstration Build. Qualification of an AM machine operator requires that the operator complete a demonstration build in accordance with a qualified AMPS for the highest classification component for which the operator is qualifying (e.g., an AM machine operator qualification build using a Class A qualified AM procedure is required to qualify a Class A AM machine operator). The demonstration build shall be inspected in accordance with the requirements of Clause 8 for the relevant component classification. An AM procedure qualification preproduction test build for the relevant component classification may be used for the AM machine operator qualification demonstration build provided that the preproduction test build meets all acceptance criteria.

6.3.5 Partial Requalification. Any change in AM machine software version that involves operator actions requires partial requalification to demonstrate operator understanding. This partial requalification shall consist of the completion of a minimum of four hours of training and the completion of a demonstration build in accordance with 6.3.4.

6.4 Maintenance of Qualification. AM machine operator qualification is maintained by successfully completing an AM build using the AM machine model for which the operator is qualified at least once within a 6-month period. Documentation of AM builds completed to maintain AM machine operator qualification shall be included in the qualification records (6.6).

6.5 Qualification Expiration. An AM machine operator's qualification expires:

- (1) When employment with the Contractor is terminated
- (2) When the AM machine operator has not operated the AM machine for which they have been qualified within a 6-month period
- (3) When requalification is not performed as required by 6.3.5 for AM machine software version changes
- (4) When there is specific reason to question the AM machine operator's ability to fabricate AM components in accordance with this standard

6.6 Qualification Records. The Contractor shall be responsible for maintaining records for each qualified AM machine operator that include the following information:

- (1) Name of employee and qualification level for each AM machine model and software version
- (2) Any limits of qualification for the AM machine operator (if not qualified for all aspects of AM machine operation)
- (3) The applicable version of the Qualification Program to which the operator qualified
- (4) Record documenting the completion of required training, signed by the Qualifier
- (5) Results of written and practical examinations, signed by the Qualifier
- (6) Record of demonstration build, including the qualified AMPS used and certification of acceptable inspection results
- (7) Records of AM builds completed to maintain qualification
- (8) Certification record signed by the Qualifier to document completion of AM machine operator qualification for a given AM machine model and software version, with a description of any limitations to the operations for which the AM machine operator is qualified

7. Fabrication

7.1 Scope. This clause establishes requirements for the fabrication of additively manufactured components.

7.2 Digital Control Plan. The Contractor shall create a digital control plan that provides a method for tracking the digital files necessary to fabricate an AM build. The digital control plan shall encompass the creation of the build files through installation of the build files onto the AM system. The digital control plan shall detail control measures necessary to ensure that the build files and any dependent files called by the build files (e.g., program files, subroutines, and/or procedural files) are the correct files to create a build in accordance with the AMPS and that the files have not been altered from the files used to create the preproduction test piece. The digital control plan shall be provided to the Engineer for review upon request. The digital control plan shall include the following:

- (1) Name and revision level of individual component surface model (e.g., STL, AMF)
- (2) Name and revision level of build parameter files
- (3) Build file processing software and revision level
- (4) AM machine software and revision level
- (5) Description of the means for ensuring that the same build parameter file is used for the production builds as was used for the procedure qualification build.

7.3 Additive Manufacturing System. A preproduction maintenance checklist shall be developed and used by the Contractor that includes the manufacturer's guidelines for each piece of equipment in the AM system. Periodic AM system checks and maintenance shall be performed, at a minimum, in accordance with the manufacturer's recommendations (such as the replacement of powder spreading blades or rollers, cleaning of nozzles, cleaning optical elements, replacement of coolant levels, gas supply, etc.).

7.3.1 Calibration and Confirmation

7.3.1.1 Calibration Control Plan. The Contractor shall establish and maintain a calibration control plan to ensure that the AM system will be capable of producing AM components that meet the requirements of the AMPS and the acceptance criteria of Clause 8. Required calibrations or confirmations shall also be performed when any changes are made to the power supply or major equipment subcomponents identified in 5.4.3 and 5.4.10. The calibration control plan shall include the following:

- (1) Power supply or major equipment subcomponents requiring calibration
- (2) Maximum calibration interval
- (3) Acceptable range for calibrated performance attributes
- (4) Maintenance checklist

7.4 Additive Manufacturing Feedstock and Build Platform

7.4.1 Identification. The Contractor shall have a documented plan for identifying feedstock and build platforms used for the fabrication of AM components. If the identification marking is destroyed or missing, the feedstock or build platform shall not be used. Traceability of the feedstock and build platforms shall be maintained throughout the AM process, including processing history on any used powder.

7.4.2 Storage, Use, and Preparation

7.4.2.1 Surface Cleaning and Other Preparation. The build platform shall be visually free from oxides, scale, protective finishes, oils, grease, dirt, or any other contaminants.

Chlorinated solvents or methyl alcohol shall not be used when cleaning stainless steel, titanium, or titanium alloys.

Austenitic stainless steel wire brushes or carbon steel wire brushes may be used on carbon or low alloy steels. Only austenitic stainless steel wire brushes or titanium wire brushes shall be used on all other materials. Once an individual wire brush is used on a certain material group (e.g., titanium, aluminum, nickel-base alloys), it shall be suitably identified and used only on that material group.

Interpass cleaning, if necessary, shall be in accordance with the qualified AMPS.

7.4.2.2 Build Platform. The build platform thickness shall be recorded in the fabrication records and shall be within the thickness range of the qualified AMPS. The build platform shall meet all surface finish and parallelism requirements of the AMPS.

7.4.2.3 Feedstock (1) Powder. The powder specification shall contain requirements and tolerances for chemical composition, particle size distribution, particle morphology, rheological performance, and any other characteristics as agreed upon by the Engineer and Contractor.

For particle size distribution (PSD), the powder specification shall contain information regarding sieving operations, $d_{2,10,50,90,98}$ values, and particle morphology (e.g., circularity, sphericity, convexity), characterized through laser diffraction or another optical method with similar resolution. The powder specification shall also include the number-weighted histogram of the actual PSD that is used to generate the required values. All values shall be within the acceptable tolerances as agreed upon by the Engineer and Contractor.

For rheological performance, the powder specification shall contain the apparent density, as well as one of the methods from the following list:

(1) Bulk Flow Energy (BFE) and Specific Energy (SE) obtained through powder rheometry in accordance with the procedures established by the rheometer's manufacturer.

(2) A Mohr's Circle analysis obtained through powder shear testing including angle of internal friction, yield stress, and cohesion.

(3) For L-DED only, aeration testing obtained through rheometry in accordance with the procedures established by the rheometer's manufacturer.

(4) Angle of repose

The required information shall be recorded in the AMPS. Powder is considered to be potentially deviated from the acceptable tolerances, as agreed upon by the Engineer and Contractor, and must be reevaluated if it has been in storage for greater than six months, is of a different lot, or has undergone any recycling, reconditioning, blending, or mixing processes.

Prior to any build that occurs after a deviation as described above, the starting powder to be used for the next component build must be sampled in accordance with ASTM E2651, *Standard Guide for Powder Particle Size Analysis* and ASTM B215, *Standard Practices for Sampling Metal Powders*, and tested for the variables identified for the powder specification in accordance with the AMPS. If all values are not within the established acceptable tolerances, requalification is required in accordance with Table 5.2 or Table 5.3. Each of the powder characteristic values and powder lot(s) shall be identified in the AMPS and recorded in the fabrication records.

Powder handling and equipment shall not cause contamination or cross contamination. Powder handling and usage including sieving, blending, and recycling of powder shall meet the requirements of the AMPS. Powder feedstock material shall be stored in a clean and dry environment. Blending of multiple powders at the build platform shall meet the requirements of the AMPS. Powder shall be handled and stored according to manufacturer's recommendations.