



AEROSPACE MATERIAL SPECIFICATION

AMS7032™

Issued

2022-08

Machine Qualification for Fusion-Based Metal Additive Manufacturing

RATIONALE

Metal additive manufacturing (AM) machine qualification requirements are process intensive. This document is intended to provide technical information on the requirements for qualifying a metal AM machine that is suitable for producing aerospace-grade material. Thus, the intended users of this document are organizations that will directly produce these aerospace-grade parts, or by those responsible for overseeing their production and therefore have a vested interest in verifying the performance of additive manufacturing machines.

1. SCOPE

This standard has notes/guidance narratives interspersed throughout. These notes/guidance narratives are identified by a header and by text in *italics*.

This standard defines a series of requirements that results in a specific AM machine qualified to produce material (see *GN1*) in compliance to an aerospace materials specification. The machine control and/or configuration types are discussed in the next sections. The industry (including AIA and ASTM) generally acknowledges that there are three qualification milestones for AM machines; nevertheless, this document will focus only on the initial two stages, namely:

- Installation Qualification (IQ): Producing objective evidence to show that all key aspects of the process equipment and ancillary system installation adhere to the AM Part Producer's specification and that the recommendations of the supplier of the equipment are suitably considered; this is tied to a specific machine serial number.
- Operational Qualification (OQ): Establishing sufficient process control to maintain stable material performance and demonstrating that the material specification requirements can be met; this is also tied to a specific machine serial number (see *GN2*).

[GN1] Guidance Notes:

For the purposes of this document, "material" refers to consolidated material produced during the AM process, not to be confused with the raw feedstock.

[GN2] Guidance Notes:

Qualification does not end with OQ. Discussion on the final qualification milestone, Performance Qualification (PQ) is outside the scope of this document, although an overview is provided in 9.1. Similarly, Material Qualification (MQ) is summarized in brief as part of the PQ process. It is important to note that each of these qualification milestones may have slightly different considerations based on the machine control and/or configuration types.

SAE Technical Standards Board Rules provide that: "This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user."

SAE reviews each technical report at least every five years at which time it may be revised, reaffirmed, stabilized, or cancelled. SAE invites your written comments and suggestions.

Copyright © 2022 SAE International

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of SAE.

TO PLACE A DOCUMENT ORDER: Tel: 877-606-7323 (inside USA and Canada)
Tel: +1 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
http://www.sae.org

SAE WEB ADDRESS:

Full document details: SAE AMS7032

For more information on this standard, visit
<https://www.sae.org/standards/content/AMS7032/>

Documents

Document Sharing Hub

1.1 Machine Control Types

1.1.1 Fixed-Parameter Machines

Fixed-parameter machines are AM machines where the parameters are locked in at any point prior to initiation of the build cycle.

1.1.2 Adaptive-Parameter Machines

Adaptive-parameter machines are AM machines that operate with a control system that varies the parameters (during a build) within a fixed process window based on real-time feedback within the system. The overall qualification approach for adaptive-parameter machines is essentially the same as for fixed-parameter machines, but the adaptive control will drive a more in-depth process window development and analysis, as well as statistical process control (SPC) and perhaps other aspects. The specifics of how the approaches vary depend on the level of adaptive-parameter control, which parameters are adaptive, etc.

1.2 Machine Configuration Types

In general, this standard applies to powder bed fusion (PBF) and wire- or powder-fed directed energy deposition (DED) technologies. Plasma, electron beam or lasers are applicable energy source(s) for melting (see GN3).

[GN3] Guidance Notes:

At the time of this standard's publication, these are the machine configurations that are covered:

Electron Beam Powder Bed Fusion (EB-PBF) - Additive manufacturing process in which thermal energy supplied by one or more electron beam(s) selectively fuses regions of a powder bed (refer to AMS7007).

Laser Powder Bed Fusion (L-PBF) - Additive manufacturing process in which thermal energy supplied by one or more laser(s) selectively fuses regions of a powder bed (refer to AMS7003).

Electron Beam Directed Energy Deposition-Wire (EB-DED-Wire) - Additive manufacturing process in which a focused beam of electrons is used to locally melt and deposit wire to form three dimensional shapes (refer to AMS7027).

Wire Fed Plasma Arc Directed Energy Deposition (PA-DED) - Additive manufacturing process in which focused thermal energy supplied by one or more plasma arc(s) is used to fuse wire by melting as it is being deposited (refer to AMS7005).

Laser Directed Energy Deposition with Wire (L-DED-Wire) - Additive manufacturing process in which focused thermal energy supplied by one or more laser(s) is used to fuse wire by melting as it is being deposited to form three-dimensional shapes (refer to AMS7010).

Laser Directed Energy Deposition with Powder (L-DED-Powder) - Additive manufacturing process in which focused thermal energy supplied by one or more laser(s) is used to fuse powder by melting as it is being deposited to form three dimensional shapes (refer to AMS7010).

1.3 Safety - Hazardous Materials

While the materials, methods, applications, and processes described or referenced in this standard may involve the use of hazardous materials, this standard does not address the hazards which may be involved in such use. It is the responsibility of the user to ensure familiarity with the safe and proper use of any hazardous materials and to take necessary precautionary measures to ensure the health and safety of all personnel involved, while ensuring any hazardous waste generated is handled and disposed of in accordance with local regulatory requirements.

2. APPLICABLE DOCUMENTS

The issue of the following documents in effect on the date of the purchase order forms a part of this standard to the extent specified herein. The AM Part Producer may work to a subsequent revision of a document unless a specific document issue is specified. When the referenced document has been cancelled and no superseding document has been specified, the last published issue of that document shall apply.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AMS7003	Laser Powder Bed Fusion Process
AMS7005	Wire Fed Plasma Arc Directed Energy Deposition Additive Manufacturing Process
AMS7007	Electron Beam Powder Bed Fusion Process
AMS7010	Laser Directed Energy Deposition Additive Manufacturing Process (L-DED)
AMS7027	Electron Beam Directed Energy Deposition-Wire Additive Manufacturing Process (EB-DED-Wire)
AIR7352	Additively Manufactured Component Substantiation
AS7766	Terms Used in Aerospace Metals Specifications

2.2 AIA Publications

Available from Aerospace Industries Association, 1000 Wilson Boulevard, Suite 1700, Arlington, VA 22209-3928, Tel: 703-358-1000, www.aia-aerospace.org.

AIA Report, 2020 Recommended Guidance for Certification of AM Components

2.3 AWS Publications

Available from American Welding Society, 8669 NW 36 Street, #130, Miami, FL 33166-6672, Tel: 1-800-443-9353 or 305-443-9353, www.aws.org.

AWS D20.1 Specification for Fabrication of Metal Components Using Additive Manufacturing

2.4 ISO/ASTM Publications

Available from International Organization for Standardization, ISO Central Secretariat, 1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, Tel: +41 22 749 01 11, www.iso.org.

ASTM E8	Standard Test Methods for Tension Testing of Metallic Materials
ISO/ASTM 52900	Additive manufacturing - General principles - Terminology
ISO/ASTM 52921	Standard terminology for additive manufacturing - Coordinate systems and test methodologies
ISO/ASTM 52942	Additive manufacturing - Qualification principles - Qualifying machine operators of metal powder bed fusion machines and equipment used in aerospace applications

2.5 DIN Publications

Available from DIN, www.din.de.

- DIN 65123 Methods for Inspection of Metallic Components, Produced with Additive Powder Bed Fusion Processes
- DIN 65124 Aerospace Series - Technical Specifications for Additive Manufacturing of Metallic Materials with the Powder Bed Process

2.6 Industry Publications

Available from Battelle Memorial Institute, 505 King Avenue, Columbus, OH 43201, Tel: +1 614-424-6557, www.mmpds.org.

- MMPDS Handbook Metallic Materials Properties Development and Standardization

2.7 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report. This is not intended to be an all-inclusive list of publications that may be informative.

2.7.1 ANSI Accredited Publications

Copies of these documents are available online at <https://webstore.ansi.org/>.

- ANSI Z136.1 Safe Use of Lasers

2.7.2 ISO/ASTM Publications

Available from International Organization for Standardization, ISO Central Secretariat, 1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, Tel: +41 22 749 01 11, www.iso.org.

- ISO/ASTM 52941 Additive manufacturing - System performance and reliability - Acceptance tests for laser metal powder-bed fusion machines for metallic materials for aerospace application
- ISO 11554 Optics and photonics - Lasers and laser-related equipment - Test methods for laser beam power, energy and temporal characteristics
- ISO 11146-1 Lasers and laser-related equipment - Test methods for laser beam widths, divergence angles and beam propagation ratios - Part 1: Stigmatic and simple astigmatic beams
- ISO 11146-2 Lasers and laser-related equipment - Test methods for laser beam widths, divergence angles and beam propagation ratios - Part 2: General astigmatic beams

2.7.3 NFPA Publications

Available from NFPA, 1 Batterymarch Park, Quincy, MA 02169-7471, Tel: 617-770-3000, www.nfpa.org.

- NFPA 484 Standard for Combustible Metals

2.7.4 OSHA Publications

Available from U.S. Department of Labor/OSHA, 200 Constitution Avenue, Washington, DC 20210, Tel: 800-321-6742, www.osha.gov/pls/publications/pubindex.list.

- OSHA 3371 Hazard Communication Guidance for Combustible Dusts

3. TECHNICAL REQUIREMENTS

3.1 Establishing Installation Qualification (IQ)

Installation qualification is machine-serial-number-dependent, meaning that each serialized machine shall be qualified (see *GN4* and *GN5*). Active qualification status of an AM machine is established initially through the following:

1. Verify that the AM machine is in a calibrated state with updated maintenance in accordance with the calibration and maintenance requirements of the applicable SAE AMS specification (or equivalent, when authorized by the Cognizant Engineering Organization (CEO)). Standards traceable to NIST (National Institute of Standards and Technology) or equivalent National Standard shall be used for all calibrations when available. If such a standard is not available, the methodology used for calibration shall be authorized by the CEO. Any sensor that measures a KPV (Key Process Variable) from 3.2 shall be included in calibration. The calibration shall meet the requirements of the Calibration and Verification Plan in 3.2.2.4.
2. It is recommended, but not required, to establish and perform Site Acceptance Test (SAT) - A site acceptance test build(s) should:
 - a. Cover the full build area for each energy source with parts, specimens, or artifacts that verify the following:
 - i. Machine calibration - laser power, spot size, gas flow, laser overlap, etc.
 1. Could be partially verified through examinations such as positional accuracy in all axes (geometric features), surface finish, part density and/or porosity, etc.
 - b. A single IQ may be performed, regardless of the number of materials or unique parameter sets that will be used in the future.
 - i. If the machine is from a machine OEM (not built by the AM Part Producer), then the machine OEM SAT build or other approved builds shall be printed and evaluated per the machine OEM recommendations. Acceptance criteria shall be agreed upon prior to SAT build by machine OEM and AM Part Producer. If the evaluations pass, then the installation qualification is complete.
 - ii. If the machine was built by the AM Part Producer, then a standard build shall be printed and evaluated. If the evaluations pass, then the installation qualification is complete.
3. If any of the tests or analyses do not meet expectations, define cause for rejection and successful completion of SAT build after corrective action is applied.
4. Record the active installation qualification status in an AM machine configuration log (see *GN6*).

[GN4] Guidance Notes:

The installation qualification by the machine manufacturer and AM part producer is the first step in establishing machine qualification. The installation qualification is used to ensure the machine meets a minimum standard and sets the base line for additional, more stringent machine and performance qualifications and system checks to monitor the state of the machine. It is common for a test build to be conducted at the factory to provide objective evidence of efficacy of the system as configured. It is common for AM Part Producers to build sample test parts representative of the components they intend to produce at this stage of qualification. Some components and alloy combinations will require iteration to produce an acceptable result which should be well understood before material qualification is executed.

[GN5] Guidance Notes:

It is recommended to make considerations for the Facility Control Plan (discussed in 3.2.2.3) prior to and during IQ. The plan will then be finalized and put in place for OQ.

[GN6] Guidance Notes:

Consideration should also be made for proper cleaning of the machine after completion of IQ if a different feedstock is to be used after IQ.

3.2 Establishing Operational Qualification (OQ)

Prior to pursuing operational qualification, the installation qualification in 3.1 shall be complete. Operational qualification is machine-serial-number-dependent, meaning that each serialized machine shall be qualified to a process specification for each material.

The initial machine(s) of a particular make and model that are qualified shall develop the ranges for the process window of the Key Process Variables (KPVs), which are generally listed in the applicable AMS process specification (see *GN7*). To ensure consistent performance, KPVs shall be identified, associated tolerance bands determined (process window), and the impact of variation through each tolerance band should be understood. Testing shall focus on these KPVs that strongly correlate with desired characteristics of finished part, such as mechanical (e.g., static strength, fatigue, fracture), metallurgical, physical, or chemical properties. Despite there being many discrete parameters controlling most additive manufacturing processes, the actual number of parameters critically influencing performance is typically a more limited subset. The AM Part Producer shall demonstrate which parameters, and interactions thereof, are critical to the process (i.e., KPVs) and which are not, and implement appropriate control plans for both. The KPV list and process window shall be authorized by the CEO.

[GN7] Guidance Notes:

When demonstrating which parameters and interactions are critical to the process, a design of experiments (DOE) can be useful for this purpose. As an example of an interaction, laser power and scan speed may be KPVs on their own, and their interaction may also be critical to the process.

The intent of operational qualification is to: establish process control, calibration, maintenance, and adjustment requirements to ensure stable material performance. Machine OQ is the process by which a machine is qualified to a given material specification (e.g., AMS7000). These controls will become Process Control Documents (PCDs) as part of the Performance Qualification (see 9.1.3). If a new machine parameter set (beyond the KPV ranges defined and approved in the process PCD that was used for the existing OQ) or new feedback/control algorithms or constants (for adaptive-parameter machines) are developed for production use, a new OQ shall be performed using Table 1 criteria for 1st OQ for specific material specification and KPV process window combination.

The AM Part Producer shall run a series of metallurgical, mechanical, and physical property tests on each serialized machine to ensure the machine meets the applicable material specification(s) throughout the process window established by the first qualified machine of that make and model. Data history and tracking may be required to set limits for other KPVs. OQ builds (see 3.2.2) should be used to demonstrate material performance and may include artifacts to validate other metallurgical, dimensional, and/or surface roughness characteristics. The OQ build test results shall be included in required Statistical Process Control (SPC) practices (see *GN8*). OQ has been completed when it has been demonstrated that the material specification requirements can be met by the serialized machine with statistical relevance over multiple builds.

[GN8] Guidance Notes:

Including OQ builds in SPC establishes a baseline for SPC and a recurring checkpoint during required, periodic requalifications, as well as production lot acceptance. If a machine is qualified for more than one build layout, each build layout may have slightly different thermal histories, etc., that could mask gradual process drift. Periodically building the standard OQ build will ensure that gradual process drift is not missed.

3.2.1 Process Control Documents (PCDs)

All PCDs shall be established by the AM Part Producer, substantiated with respect to the specified requirements, and authorized by the CEO. Once substantiated, all aspects of the PCDs are considered to be a fixed process and any changes to a PCD shall require substantiation prior to the change being implemented into production. Changes to any PCD that can affect a Key Process Variable shall be authorized by the CEO. All other changes to the PCD shall be acceptable to the CEO. In general, the PCDs shall address the following aspects of the Additive Manufacturing Machine Qualification process (see 3.2.1.1 to 3.2.1.5). All PCDs listed in this section and sub-sections for the Machine Qualification process shall be in place to support the process control necessary for OQ, prior to performing any builds for OQ. Additionally, the AM Part Producer should recognize that it may be necessary to change these PCDs to meet MQ and PQ requirements. The OQ process controls become fixed as part of PQ.

3.2.1.1 Work Instruction Plan

Detailed operational procedures for all AM machines and associated equipment shall be documented in the form of checklists or other suitable means that ensure facility operations are standardized to the fullest extent possible and that provide operators a convenient method to ensure all procedural steps are completed. Consistency in the execution of sensitive processes, such as AM, is critical to maintaining control. Formalized procedures and checklists for complex operations are the key to achieving operational consistency.

Procedural work instructions or checklists are the responsibility of the AM Part Producer and may be implemented in any manner suiting the operational norms of the facility. Procedures or checklists are intended to be sufficiently detailed that they are fully specific to a given machine or piece of equipment and are intended to be in place for all standard and readily foreseen contingency situations arising in normal operations such as powder handling/filling, build set up and execution, build completion and removal of parts, powder removal from parts, machine cleaning, and other such common operations.

3.2.1.2 Machine Configuration Plan

A machine configuration plan for each AM machine shall be maintained. The machine configuration shall be locked once qualified. The machine configuration plan should address configuration control of both the machine hardware (make, model, and serial number) and software (defined by both the machine OEM and the AM Part Producer). For each serialized machine, a log should be created and include, at minimum, the following events: maintenance, calibration, and qualification, machine manufacturer service calls, repairs or other changes to machine, updates to machine, monitoring and build software and firmware versions.

Maintaining an accurate record of machine configuration is necessary to (1) establish the state of the AM machine at the time of qualification, (2) track or identify machine changes that may influence qualification status and the quality of the AM process, and (3) prevent unplanned or unintended loss of configuration control. Loss of AM machine configuration control negates the process control logic at the foundation of these requirements.

3.2.1.3 Installation and Operating Conditions Plan

The AM Part Producer shall develop a facility control plan to verify the following:

- Installation and operating conditions: temperature, humidity, sources of dynamic electromagnetic interference, floor profile and level meet machine OEM guidelines.
- Hazardous and/or reactive material storage locations and quantity limits.
- Utility availability: required process gasses, power, chill water, etc. are available at required quantity or rating.
- Ventilation needs and byproducts produced by AM equipment meet all applicable environmental and safety standards.
- Hazard mitigation systems such as fire protection and electrostatic grounding are consistent with OEM recommendations and all applicable environmental and safety standards.

3.2.1.4 Calibration and Verification Plan

Calibration and verification of AM machines and associated equipment is a prerequisite to establishing the qualification of machines for production (see *GN9*). The applicable AMS AM process specification (or equivalent, when authorized by the CEO) provides minimum requirements for a calibration and verification plan. The results of calibration shall be documented. At a minimum, the documentation shall include:

- a. Unique identification of the instrument.
- b. Make and model of the instrument calibrated.
- c. Unique identification of the test instrument used during calibration.
- d. Identification of each sensor type in use (e.g., type K, N, etc.) and form (e.g., V, mA, etc.) if the instrument is used for these scales.
- e. Required calibration accuracy.
- f. As-found data at each calibration point and as-left data if any adjustments are made, to include:
 1. Nominal test temperature.
 2. Error of test instrument (optional or when specified by the CEO).
 3. Error of test instrument under test (corrected or uncorrected for test instrument error when specified).
- g. Correction and modification offsets as-found and as-left.
- h. Sensitivity, pass/fail (applicable to analog instruments only).
- i. Instrument calibration pass or fail statement.
- j. Any limitations or restriction of the calibration.
- k. Date the calibration was performed.
- l. Due date of the next calibration.
- m. Statement of traceability to NIST or other internationally recognized standards organization, when available.
- n. Identification of the technician who performed the calibration.
- o. Identification of the calibration agency if calibration is not performed internally.
- p. Approval of an authorized agent for the calibration agency, if performed by a third party.
- q. User quality organization approval.

[GN9] Guidance Notes:

In certain situations, it may be necessary to use validation methods for calibration. Three examples include laser power, beam spot size and beam travel speed, where calibration devices and methods may be used to measure/validate an output, such as laser power, spot size or scan speed, for a given input, such as laser power setting, spot size setting or scan speed setting, respectively. The results of this validation process are then used to calibrate the system by applying correction factors to the inputs to attain the desired outputs, e.g., the use of a lookup table which correlates the appropriate correction factor for a given set point to attain the desired output.