Additive Manufacturing Industrial Standards for Production Process Capability – Polymer Powder Bed Fusion

Process Capability, Safety, and Operating Standards

Table of Contents

1. Scope

This document outlines the requirements for the initial and continued qualification of polymer powder bed fusion machines for additive manufacturing of automotive applications. This standard is to be used to qualify machine and process capabilities, provide operating requirements involving safety systems, and outline requirements for operating standards of these systems. Further, this standard is to be used to re-qualify equipment on a periodic basis, including but not limited to periodic inspections, following maintenance, and following repair procedures. This standard can be applied during any phase of machine commissioning or requalification. This document scope does not include all the general safety, operating, and IT requirements that are required and established for all manufacturing systems. The general requirements shall be listed in a statement of requirements (SOR) that shall be issued by each Owner.

2. Definitions

- Polymer Powder Bed Fusion – classification of additive manufacturing technologies in which thermal energy selectively fuses regions of thermoplastic powder layer by layer in a powder bed.
- Owner – entity or entities operating polymer powder bed fusion equipment.
- OEM – machine original equipment manufacturer responsible for providing polymer powder bed fusion equipment.
- Supplier – entity responsible for providing polymer powder bed fusion equipment. May be machine OEM or distributor.
- Build Envelope – largest dimensions of the x, y, and z axes within the build space where acceptable parts can be fabricated. Defined by the manufacturer; also called buildable volume.
- Build Space – location where it is possible for parts to be fabricated, typically within the build chamber, including the space outside of the manufacturer recommended build envelope.
- Build Platform – base of a build space which provides a surface upon which the building of the part(s) is started and supported throughout the build process.
- Build Variability Geometry (BVG) – geometry designed to test dimensional variability.
- Build Variability Geometry Set (BVG Set) – set of BVGs oriented in 3 unique orientations (specified in standard).
- Factory Acceptance Test (FAT) – name of the machine buyoff standard.
- Tensile Bar (ISO 527 1BA) – specimen defined by ISO 527 for mechanical testing.
- Tensile Bar Set – set of tensile bars oriented in 3 unique orientations (specified in standard).

- Machine origin – machine home, or zero point as defined by the machine manufacturer.
- Front – side of the machine that the operator faces to access the user interface or primary viewing window.
- Bottom – build platform at home position with z-axis at the origin.
- Home – lowest z position; z=0.

3. Machine Qualification

3.1 Machine Conditions

The supplier is responsible for providing a machine that has been properly vetted for performance, prior to delivery to the machine owner. This includes, but is not limited to, the performance of the laser or fusing system, powder delivery mechanisms, and other equipment or machine functions considered to be the responsibility of the machine supplier.

For purposes of system evaluation, equipment shall be installed according to manufacturer's documented instructions, unless otherwise approved or specified by the owner. This includes the environmental and operational conditions, which shall be within the requirements of the machine OEM. These conditions shall include, but are not limited to:

- Relative humidity
- Temperature
- Compressed air supply
- Gas supply
- Vibration isolation
- Ventilation
- Air quality
- UV light exposure

All operations for which personnel are exposed to hazards shall follow proper safety procedures, including but not limited to proper personal protective equipment. **Failure to adhere to suitable safety procedures is grounds to consider the Acceptance Testing Evaluation as a failure.** Fire, explosion, laser radiation, and all other hazards must be protected against.

During evaluation, any relevant machine setup fixed parameters are to be marked for future reference. This can include but is not limited to set points for pressure regulators, critical bolts for torque reference, sensor locations, etc.

3.2. Qualification Conditions

To demonstrate the capability of the machine, qualification builds will be conducted. These builds are intended to demonstrate the capabilities of the machine to provide repeatability and reproducibility in the areas of dimensional performance and mechanical property performance, as a function of both orientation and build space location.

In addition, this qualification build will certify the build envelope (also known as the buildable volume) and capacity of the equipment, as supplied by the machine manufacturer under normal operating conditions.

Qualification builds are to be performed using OEM defined material parameter sets and OEM defined material feedstock, where applicable. A material feedstock powder certification report is to be provided to the machine owner for reference. All subsequent steps following the printing process are to be standard machine OEM recommendations, unless otherwise specified by the machine owner. This includes but is not limited to build cooling, depowdering, and other post-processing procedures.

The standard build parts include dimensional artifacts and mechanical property specimens.

Machine qualification will address mechanical and dimensional performance of prints; and will also assess variability from location to location within the build envelope, from build to build in the same printer, and from machine to machine, when applied to multiple systems.

3.3. Mechanical Testing

Mechanical performance will be assessed per ISO 527-1/2; Test speed will be 50 mm/minute for tensile strain at yield or break > 10 %.; Test speed will be 5 mm/minute for tensile strain at yield or break < 10 %. If a new ISO standard for polymer powder bed fusion tensile testing has been published after the publication of this standard, that method may be used in lieu of ISO 527. A set of tensile bars oriented with the x, y, and z axis coordinates shall be defined as a Tensile Bar Set (see Figure 1). This Tensile Bar Set can be found at https://uscar.org/publications, referenced as 'ISO_1BA_Set_Coupon_V6'.

Specimen: ISO 527-1/2, 4 mm thick Type 1BA bar

Performance Requirement: Must meet or exceed performance requirements for elastic modulus, yield strength, ultimate tensile strength, and % total elongation as defined by owner specification.

3.4. Dimensional Performance Testing

Variability of dimensional performance will be assessed by defining a build variability geometry (BVG) shown in Figure 2. The effects of orientation and location within the build envelope (buildable volume) on the dimensional performance will be assessed by examining BVGs. A set of BVGs with specified orientations shall be defined as a BVG set (see Figure 3). The BVG can be found at https://uscar.org/publications, referenced as 'AM_Standards_Test_Geometry'.

Specimens: Build Variability Geometry (BVG)

Performance Requirement: Must meet or exceed all dimensional requirements as defined by owner specification.

3.5 Build Layout

This standard is intended to provide guidance on the build layout required to meet the testing requirements for mechanical testing and dimensional variation outlined above. This is intended to apply to most industrial systems and provide guidance to the owner in creating a suitable layout. However, it is up to the discretion of the owner to apply these guidelines as they see fit, to meet their requirements in their given situation as some systems may have unique layouts that do not meet the same conditions outlined here.

The build layout recommended should attempt to test the system performance at the extents of the build envelope. Therefore, BVG sets and tensile bar sets should be placed in all 8 corners of a prismatic build envelope. For qualification procedures involving a single build, these sets should follow an alternating pattern in the x, y, and z planes, to gather data throughout the build envelope. In addition, it is preferable to include samples in the center of the build envelope where applicable. It is recommended that at least 4 each of the BVG and tensile bar sets be built and tested.

Care should be taken to maximize the number of specimens built in the qualification procedure, though the number of specimens tested is up to the discretion of the owner. The build layout should take into consideration best practices for machine performance, such as thermal distribution. Additional parts may be added for additional testing or to create a more even thermal distribution throughout the build chamber, which may or may not be tested per the discretion of the system owner.

The tensile bar set is designed to test performance of specimens aligned along the x, y, and z axes. The specimens shall be staggered such that the cross-sectional area does not exhibit large changes as the z-axis position increases (see Figure 1). The BVG set is designed to test dimensional tolerance as a function of orientation as well, with the geometry aligned in the xy plane, the yz plane, and rotated 45 degrees about each axis. Spacing of 6 mm between individual pieces is recommended unless otherwise specified by the system OEM or owner.

A simplified example build layout is provided in Figure 44. As is shown, for a system with dimensions of 380 x 240 x 330 mm; three layers of alternating BVG and tensile bar sets can be configured with 5 sets of specimens in each of the respective xy planes. An example including the actual geometries is shown in Figure 5.

Once a build layout is used for qualification of a given system, this shall be used for qualification of all other instances of that system and shall be reused for any future machine requalification testing.

Location-to-location variability is to be assessed via qualification build. Build-to-build variability is to be assessed with an owner defined number of builds. This common procedure is applied to multiple machines for machine-to-machine performance.

Unique identifiers can be added to the part CAD prior to printing to preserve their location in the build throughout build and testing. Modeling of the unique identifiers should be done carefully as to not affect performance during measurement / testing.

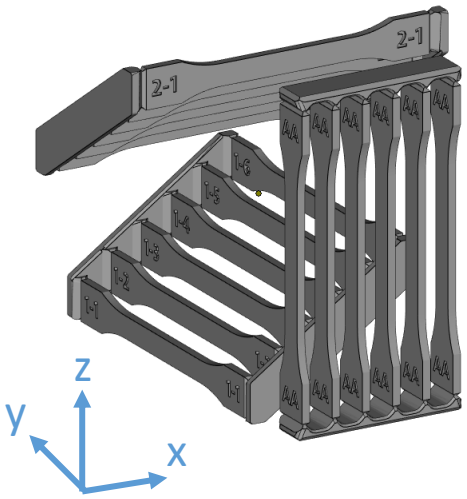

Figure 1. Tensile bar set with six ISO specimens oriented along x, y, and z axes.

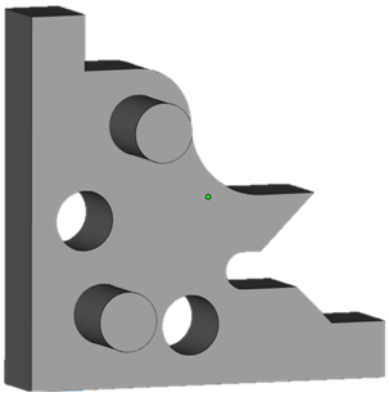

Figure 2. Build variability geometry (BVG).

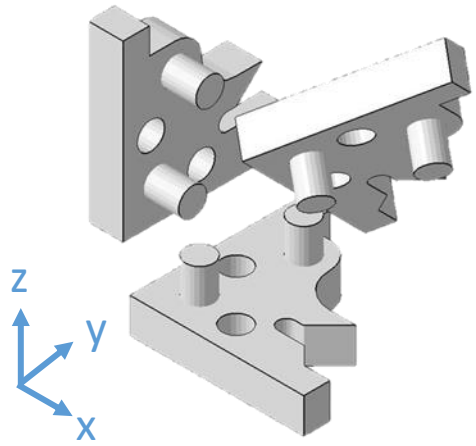

Figure 3. BVG set with three BVGs in defined orientations and spacing.

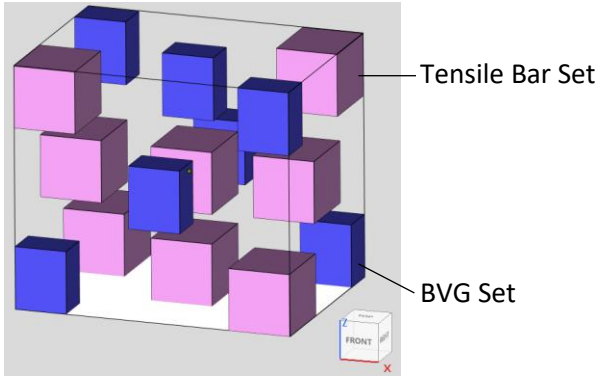

Figure 4 - Simplified build layout showing locations of tensile bar sets and BVG sets; the bounding box of the tensile bar set is shown in pink and the bounding box of the BVG set is shown in blue.

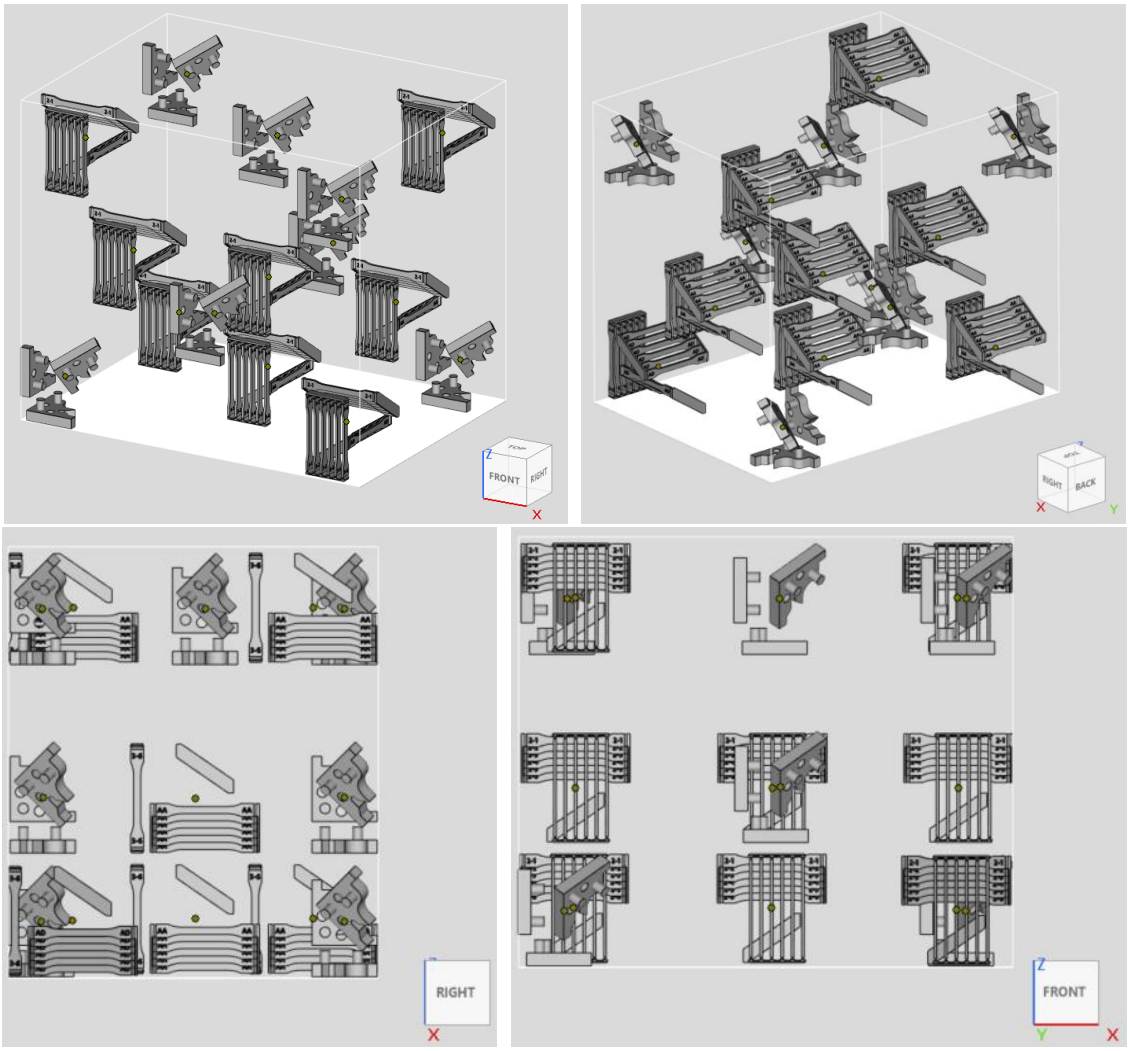

Figure 5 – Multiple views of the build layout showing location of tensile bar sets and BVG sets. Additional owner selected parts may be nested with shown layout to meet OEM recommended pack density or other requirements.

4. Safety

All safety systems shall be demonstrated and verified for proper function. This includes, but is not limited to, all machine lockouts, emergency stop functions, and electrical disconnects. Failure to exhibit proper performance in any of these functions shall empower the machine owner to reject the machine installation. All required personal protective equipment (PPE) shall be provided or recommended by the machine OEM. All related Safety Data Sheets (SDS) must be provided by the supplier or OEM prior to delivery of the equipment.

Equipment provided by the supplier must meet the highest level of appropriate safety certification as defined by the authority holding jurisdiction (AHJ). Supplier to provide the classification numbers for each piece of equipment provided to owner. A Dust Hazard Analysis must be conducted on the equipment and the results of this review must be provided to the system owner.

5. Operating Standards

The supplier is to provide a periodic maintenance task list and schedule. All operating and maintenance manuals must be provided to the machine owner, at, or prior to the system evaluation. A required and suggested spare parts list is to be provided to the system owner, including the spare parts delivery schedule.

The supplier is to provide all training requirements for proper machine operation, including basic operator training upon initial installation and buyoff of the equipment.

All required slicing software is to be provided with the machine installation. In addition, a software update procedure and/or schedule is to be agreed upon by the owner and supplier. All software updates must be instigated by the owner, no automated push or pull of software updates is permitted. Software cannot be instituted using an off-premises cloud. System software must enable Localhost micro-services and comply to 802.1x and TLS protocols. All machine networking that can be performed prior to machine installation shall be done.

The following documentation is required upon delivery and installation of the equipment:

- Safety data sheets (SDS)
- Operations manuals
- Installation conditions
- Electrical drawings
- Mechanical drawings – including inert gas, pneumatics, etc.
- Spare parts list
- Maintenance schedule

5.1. System Function Testing

In addition to the performance of the machine and testing through Qualification Testing, machine functions are to be tested to confirm proper operation as well. These tests may vary based on machine design with some functions not applicable for a given design. The specific tests will need to be modified for a given machine architecture or design.

All standard owner machine buyoff requirements shall be met (i.e., ergonomics assessments, noise, etc.).

System Functions:

- Build platform leveling – the build platform shall be validated to within the OEM specified tolerance requirement
- Machine motion without fault
    - Motion – all machine motion in manual and automatic modes shall be validated to operate without failure

    - Marriage – any operations which require connection between machine modules (build frames, docking stations, etc.) shall be validated and operating properly for all units in the system
- Thermal uniformity
    - Specific heater checks for temperature – any heating elements shall be validated to proper operation and reach required temperatures as specified in the process and throughout the build chamber
- Fault recovery
    - OEM shall provide a list of recoverable machine faults
    - All recoverable machine faults shall be properly recoverable
    - Any E-stop fault shall be safely cleared
- Pneumatic/hydraulic plumbing – all pneumatic/hydraulic plumbing shall be verified for proper installation
- Electrical wiring – all electrical wiring shall be verified for proper installation
- Laser calibration – all lasers must be calibrated to be operating within OEM required conditions (e.g., laser power, accuracy, focus, spot size, etc.)
- Exchangeable functions mismatch – for modules that are not intended for interchangeability, this shall be verified such that it is not possible or suitable indication is provided
- Qualification without error – machine qualification build shall be completed without machine errors, pauses, or stoppages
- Emergency stops – function of emergency stops shall be verified for proper operation
- Machine interlocks – all machine interlocks shall be verified for proper operation
- Inadequate gas supply – for systems with compressed air or inert gases these systems will be turned off, when safe to do so, to validate the machine senses inadequate supply and stops function
- Excessive gas supply – for systems with compressed air or inert gases these systems will be over supplied, where safe to do so, to validate the machine senses excessive gas supply and stops
- Chiller function – for systems requiring chilling functionality, these systems will be turned off to validate the machine senses inadequate chilling and stops
- Exclusive control – for safety related operations putting an operator at risk, exclusive operator control is required to be maintained. This applies to both virtual access to the machine and varying modules of a given system.
- Health check following functional tests – all machine functions shall be operational following qualification testing. This includes lasers, heating elements, functions requiring machine motion, etc.

6. Requalification / Continuing Capability

To ensure continued operation of the equipment, the equipment shall be requalified by the equipment owner on a periodic basis, such as every 6 months or as specified by owner or supplier. Procedures to repeat include the above qualification build to demonstrate dimensional capability, material properties, and build space variability. The same owner selected geometries included in

the build layout for initial qualification shall be used for requalification. Likewise, this machine requalification should be conducted when any significant change to machine software could have a deleterious effect on build quality, such as in the case where machine dynamics are affected.

All safety related equipment and processes should be reviewed every 6 months, or more frequently, to ensure proper operation.

All operating standards should be reviewed every 12 months, or more frequently, to ensure they are in line with the needs of the machine owner.

Following each 6 month, or similar requalification schedule, machine performance for failed builds and scrap rate should be evaluated, to ensure proper machine performance.

7. Sources:

- ASTM 52900 – Standard Terminology for Additive Manufacturing – General Principles – Terminology
- ISO 527-1:2019 Plastics – Determination of tensile properties
- https://uscar.org/publications

8. Version

Version 1.0
Initial publication April 25, 2022