U.S. Department
of Transportation
**Federal Aviation
Administration**

Advisory Circular

Subject: Powder Bed Fusion Additive Manufacturing Process for Aircraft Engine Parts

Date: 6/23/23
Initiated By: AIR-621

AC No: 33.15-3

1 PURPOSE.

This advisory circular (AC) describes an acceptable means for demonstrating compliance with Title 14, Code of Federal Regulations (14 CFR) 33.15 for aircraft engine parts with materials produced by the powder bed fusion (PBF) additive manufacturing (AM) process. Guidance is also presented on closely related design and manufacturing aspects associated with AM.

2 APPLICABILITY.

2.1 The guidance in this AC is for aircraft engine manufacturers, modifiers, Federal Aviation Administration (FAA) aircraft engine type-certification engineers, and FAA designees. The contents of this AC do not have the force and effect of law and are not meant to bind the public in any way, and this AC is intended only to provide information to the public regarding existing requirements under the law or agency policies.

2.2 This AC is not mandatory and does not constitute a regulation. This AC describes an acceptable means, but not the only means, to demonstrate compliance to the material requirements of 14 CFR 33.15. However, if you use the means described in the AC, you must follow it in all important respects. When the method of compliance in this AC is used, terms such as “should,” “may,” and “must” are used in the sense of ensuring applicability to this particular method of compliance. The FAA will consider other means of showing compliance that an applicant may elect to present. While these guidelines are not mandatory, they are derived from extensive FAA and industry experience in determining compliance with the relevant regulations. If, however, the FAA becomes aware of circumstances that convince us that following this AC would not result in compliance with the applicable regulations, we will not be bound by the terms of this AC, and we may require additional substantiation as a basis for finding compliance.

2.3 The material in this AC does not change or create any additional regulatory requirements, nor does it authorize changes in, or permit deviations from, existing regulatory requirements.

3 RELATED READING MATERIAL.

The following materials are related to the guidance in this document. Unless otherwise indicated, you should use the current edition if following the method of compliance set forth in this AC.

3.1 Title 14, Code of Federal Regulations.

- *Part 21, Certification Procedures for Products and Parts.*
- *Section 33.15, Materials.*

3.2 Industry Documents.

Many industry standards are available (and under development) that provide additional information, guidance and standards for AM material. The following listing of industry publications from the American Society for Testing and Materials (ASTM), Battelle, International Organization for Standardization (ISO), and the Society for Automotive Engineers (SAE) represents a sample of available industry publications supporting the adoption of AM.

- ASTM F2924, *Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion.*
- ASTM F2971, *Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing.*
- ASTM F3001, *Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion.*
- ASTM F3049, *Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes*.
- ASTM F3055*, Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion.*
- ASTM F3056, *Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion.*
- ASTM F3122, *Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes*.
- ASTM F3184, *Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion*.
- Battelle, *Metallic Materials Properties Development and Standardization (MMPDS) Handbook*.
- ISO/ASTM52900, *Additive manufacturing — General principles — Terminology*.

- ISO/ASTM52915, *Standard Specification for Additive Manufacturing File Format (AMF) Version 1.2*.
- ISO/ASTM52921, *Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies*.
- ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories.*
- SAE AMS7000, *Laser-Powder Bed Fusion (L-PBF) Produced Parts, Nickel Alloy, Corrosion and Heat-Resistant, 62Ni - 21.5Cr - 9.0Mo - 3.65Nb Stress Relieved, Hot Isostatic Pressed and Solution Annealed*.
- SAE AMS7001, *Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 62Ni - 21.5Cr - 9.0Mo - 3.65Nb*.
- SAE AMS7002, *Process Requirements for Production of Metal Powder Feedstock for Use in Additive Manufacturing of Aerospace Parts.*
- SAE AMS7003, *Laser Powder Bed Fusion Process*.

4 DEFINITIONS.

- **Additive Manufacturing (AM)** – A process of joining materials to make objects from three-dimensional (3D) computer model data, usually a layer upon layer technique or method, as opposed to subtractive manufacturing methodologies.
- **Anisotropy** – Exhibiting properties with different values when measured in different directions.
- **Build Cycle** – Single process cycle in which one or more components are built up in layers in the process chamber of the additive manufacturing system.
- **Build Chamber** – Enclosed location with the additive manufacturing system where the parts are fabricated.
- **Build Platform** – A substrate on which the parts are built.
- **Debit** – A reduction applied to material strength properties to account for unique thermal exposures, design features (e.g., surface finish), operational environment, and such.
- **Design Values** – Material strength properties that are established on a statistical basis and include the effects of debits related to part features and the operational environment in which the material operates.

- **Frozen Process** – A set of identified significant process parameters required to control the fusion process to achieve the desired physical and chemical properties, material density, geometric detail, microstructure, surface condition, and other fusion-related characteristics to meet design intent in the as-built structure. Once established, these significant process parameters cannot be changed unless additional qualification is completed, which may include testing of differences.

- **Hot Isostatic Pressing (HIP)** – The simultaneous application of high temperature and pressure to metals for a specified amount of time to improve mechanical properties.

- **Key Process Variable** – An element of the AM process (e.g., build plate configuration, build layout, energy level, layer thickness, interpass time, melt pool environment, etc.) that, if changed, could affect chemical, physical, metallurgical, dimensional, or mechanical properties.

- **Mechanical Properties** – Physical properties that the material exhibits, including tensile properties, elasticity, creep and stress rupture properties, high-cycle fatigue, and low-cycle fatigue.

- **Metallurgical Properties** – Microstructural characteristics including grain size and orientation.

- **Nondestructive Inspection (NDI)** – A means of evaluating the properties of a material, component, or system without causing damage.

- **Powder Bed Fusion (PBF)** – An AM process that uses a high-energy source, such as a laser or electron beam, to selectively fuse, layer-by-layer, portions of a powder bed.

- **Powder Blend** – Quantity of powder made by thoroughly intermingling powders originating from one or several powder lots of the same nominal composition.

- **Powder Heat** – Powder from batch processes made from one melt and atomization, or powder produced during an individual production cycle from non-batch (semi-continuously melted) processes.

- **Powder Lot** – A single heat or a blend of two or more individual powder heats.

- **Powder Recycling/Powder Reuse** – The use of powder in a build that has been exposed to, one or more, previous builds in a powder bed fusion machine.

- **Process Specification** – The set of files and drawings necessary to define, run, and control all aspects of an additive manufacturing build such that the as-built parts with post processing consistently meet type design. The required process specification information may be contained in several documents including, but not limited to, part or layout drawings, process specification, process control documentation (PCD), deposition process specification, the machine build file, feedstock handling and storage plan, contamination plan, and the digital file and software configuration control plan.

- **Process Validation** – A manufacturing, quality, or engineering system for process control of a complex manufacturing process that ensures fabricated parts meet the design intent.

- **Support Structure** – An auxiliary element built concurrently with the part to provide dimensional stability during the build and/or to transfer heat away from the part as new layers are added. The support structure may be subsequently removed when required.

5 BACKGROUND.

5.1 Additive manufacturing, also known as 3D printing, refers to a range of manufacturing methods where feedstock material is consolidated by a machine using a 3D computer model into a near-finished part condition. This AC focuses on PBF AM for metallic materials, where the feedstock material in the form of alloyed or elemental powder is fused by lasers or electron beams into a near-finished final shape.

5.2 PBF AM materials are very process dependent. It is important that design values used for PBF AM materials reflect not only the variability of the feedstock materials as purchased by manufacturers, but also the variability introduced by the manufacturing process used to fabricate production parts. While PBF AM methods have many process parameters (more than 100) identified by AM experts, studies have shown that the actual number of key process variables may be much smaller. Key process variables include elements of the AM process that could affect the chemical, physical, metallurgical, dimensional, or mechanical properties of the part. Defining the key process variables for a specific AM process application, including the level of control required to yield capability for producing parts in a stable and repeatable manner, is key to successful implementation of additive manufacturing.

For life-limited parts, additional information beyond the scope of this AC may be required to demonstrate compliance with § 33.14, *Stop-start cyclic stress (low-cycle fatigue)* at amendment 33-10 (49 FR 6836, February 23, 1984) and § 33.70, *Engine life-limited parts*.

6 MATERIAL DESIGN VALUES.

6.1 Fundamentals.

6.1.1 Compliance with § 33.15 requires that suitability and durability of materials "be established on the basis of experience or tests; and conform to approved specifications." For cases where sufficient experience and/or approved specifications do not exist, material design values for AM parts should be established through test. This testing may be conducted using specimens produced with feedstock materials and process parameters representative of parameters used to produce AM parts, including post-processing operations, or with a combination of component level testing and specimen testing. Test specimens should represent multiple builds, build locations, specimen orientations (including height in the build chamber), specimen thickness, and feedstock powder lots. Resultant test specimens should conform to the material and process specifications defined for AM parts.

6.1.2 Alternately, applicants may rely on component testing supported by statistical analysis to demonstrate mechanical properties of AM parts provided that this approach fully demonstrates that final part mechanical properties meet design requirements.

6.2 Specimen Testing Considerations.

After establishing sufficient process and quality controls to consistently produce AM parts, substantiation of material design values can be achieved by testing specimens extracted from representative parts or directly produced specimens. In either case, the applicant should demonstrate that these specimens appropriately represent the variability and corresponding properties in parts fabricated by the AM production process.

6.2.1 Validating Process Windows.

Specimens used to establish material design values should address the range (i.e., window) of process variation allowed in the frozen process specification including, but not limited to the following:

- Laser or electron beams parameter windows.
- Purge gas purity possible ranges.
- Energy source performance possible ranges.
- Powder reuse possible ranges (see paragraph 8.1.2. in this AC).

6.2.2 Test and Laboratory Procedures.

The metallurgical, mechanical, and physical property test and laboratory procedures used to demonstrate the capabilities of AM metallic materials produced should conform to approved specifications and meet the following requirements:

- Laboratory and test procedures used for this purpose should be performed by a qualified laboratory that conforms to accepted standards provided by technical societies, such as the ASTM, SAE, the National Aerospace and Defense Contractors Accreditation Program (NADCAP) or equivalent.
- The test facility should demonstrate competence through International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) 17025 accreditation, or equivalent, or by a recognized accreditation body.

The applicant should identify the standards and specifications used to conduct each test procedure, including AM specific considerations when appropriate, and provide evidence of accreditation for the laboratory that performed the test.

Note: Documented company internal test standards may be used if these standards have been reviewed and accepted by the FAA. When company test standards are used, the company should have an internal process for ensuring that the testing is conducted in accordance with the prescribed test procedure.

6.3 **Building Block Approach**.

Design values should be developed as part of an overall program to establish the capability of a component to meet design objectives. Design values should be reliably established through a program of statistical analysis and a series of tests conducted using specimens of varying levels of complexity. Often referred to in industry as the "building block" approach, these tests and analyses at the coupon, details, and component levels can be used to quantify variations that could be present in the final AM part in an economically feasible manner. The lessons learned from initial tests help avoid early failures in more complex part level tests, which are costlier to conduct and often occur later in a certification program schedule. Figure 1 provides a conceptual schematic of tests included in a building block approach for a PBF AM engine component.

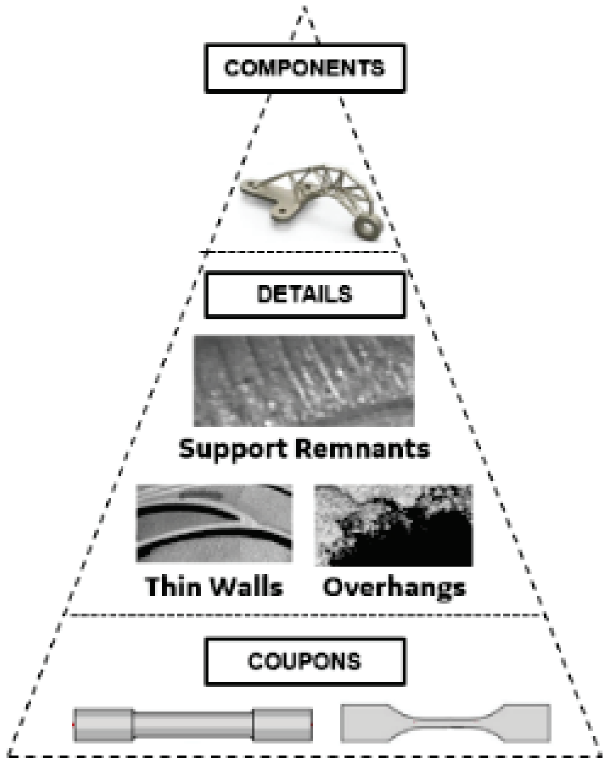

Figure 1. Schematic Diagram of Building Block Tests for an Engine Component

6.4 **Material Design Value Considerations.**

6.4.1 Material strength and design values used for AM parts need to account for variability due to the feedstock materials and production methods used to manufacture a part. In general, the variability of the material in the final part is accounted for by using statistical tools to analyze data obtained from testing of specimens extracted from actual parts or purpose-built specimens.

6.4.2 Data used to derive design values should be obtained from stable and repeatable feedstock material procured per a controlled material specification. The material should be processed with a stable and repeatable process per a representative manufacturing process specification and with process validation that establishes significant key process variables that are defined by a frozen process window. This approach ensures that the variability permitted in manufactured materials is captured in the statistical analysis used to derive the design values. Design values derived too early in the material's development stage, before feedstock material and AM part production processes have matured and are demonstrated to be stable, may not satisfy the requirements of § 33.15. As with traditional manufacturing processes, actual part design features and processing, including thermal effects, environmental effects, and geometric features that impact material properties should be addressed.

6.4.3 <u>Characterizing Material Anisotropy.</u>

Depending on process parameters, resulting parts may exhibit anisotropic material behavior. Specimen testing should be performed with specimens representing XY and Z orientations, as well as the full build height used to produce parts (see Figure 2 in this AC). If the results of this testing indicate a directional variation in properties, design values should be developed for each orientation or the orientation yielding the lowest properties should be conservatively considered when establishing the minimum baseline design values.

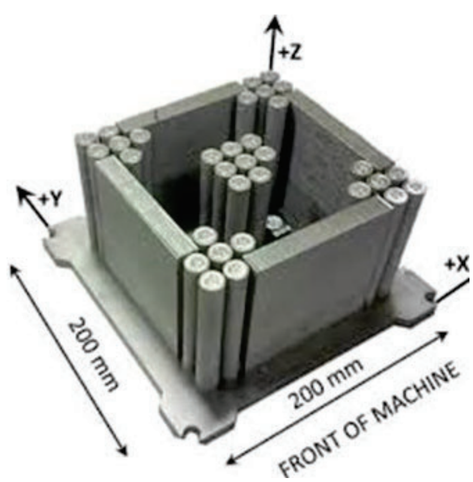

Figure 2. Orientation of XY and Z Directions

6.4.4 Establishing Design Values.

Design values are established using industry accepted solid test specimens with machined external surfaces. Material properties generated from these specimens represent material properties that can be produced with the selected feedstock material using the frozen AM process parameters including (if required) post-fabrication operations, such as stress relief cycles and other thermal cycles including HIP. Design minimums for AM materials should be established using industry accepted standards, such as the Metallic Materials Properties Development and Standardization (MMPDS) Handbook with the same rigor and requirements as minimum design values for conventionally processed materials.

Note: Design values are only applicable for AM parts that are solid, fully machined on all surfaces, and do not have geometric features that require the use of additional debits to baseline material design values.

6.4.5 Establishing Thermal Exposure Debits.

6.4.5.1 Many AM parts will have elevated temperature exposures during post-fabrication processing and/or during exposure to engine operating conditions. Examples of post-fabrication thermal exposures include thermal exposures associated with coating application and brazing cycles, HIP cycles, etc. These elevated temperature exposures can reduce actual material baseline values below minimum baseline design values.

6.4.5.2 Specimen testing should be performed with specimens processed through all required post-fabrication thermal exposures and expected operating conditions. If the results of this testing indicate a difference between design values for specimens subjected to thermal exposures and the minimum baseline design values, the results of thermal exposure specimen testing should be used to establish a thermal exposure specific debit that should be applied to the minimum baseline design values.

6.4.6 Establishing Part Feature Debits.

6.4.6.1 Depending on part complexity, AM parts may include unique features that can result in material values that are lower than the minimum baseline design values established by the data obtained from testing described in paragraph 6.4.1. Part features that can impact material values include features such as holes, internal passages, and overhanging surfaces as well as thin wall sections, stress concentrations associated with removal of supports, and as-deposited surfaces.

6.4.6.2 Specimen testing should be performed with features representative of actual features present in final parts. For example, if the final part includes as-fabricated surfaces, test specimens should be created with as-fabricated surfaces such that testing evaluates the effect of the actual part surface condition on overall material properties. If the results of this testing indicate a property debit for specimens with representative features as compared to the minimum baseline design values, the results of feature-specific specimen testing should be used to establish a feature-specific debit that should be applied to the minimum baseline design values.

6.4.7 Establishing Final Design Values.

Figure 3 depicts how the final design values are to be used with AM parts. The final design values are established by applying the debits determined by the testing described in paragraphs 6.4.5 and 6.4.6 to the minimum baseline material design values established by the data obtained from testing described in paragraph 6.4.1.

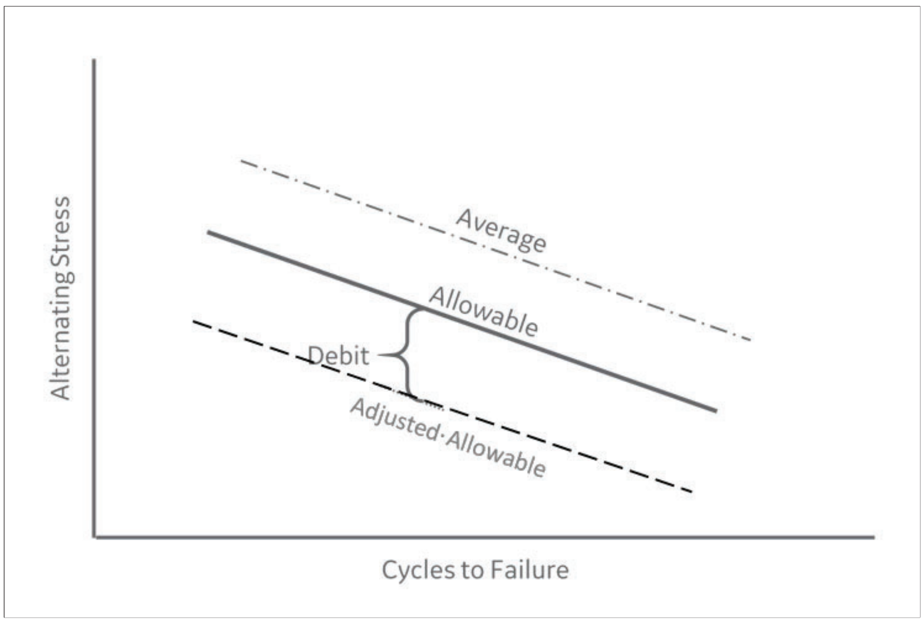

Figure 3. Example of Establishing Final Design Values

7 DESIGN CONSIDERATIONS.

7.1 Part Design Considerations.

Parts manufactured using AM require unique considerations not typically pertinent when using traditional manufacturing techniques. The resulting microstructures for AM material may vary significantly from cast or wrought microstructures for the same material. Layer-by-layer processing may generate directionally oriented microstructure that can result in both local and directional anisotropy. As with other melt processes, anomalies such as porosity, unmelted particles, and lack of fusion can occur with the AM process and should be understood and controlled. Furthermore, the physics of the layered AM process is such that anomalies tend to form along the build plane and may not have significant height in the build direction making detection difficult.

7.2 Part Orientation.

A part's orientation relative to the build platform can have a significant impact on the material properties of the final part (e.g., anisotropy, residual stress, or unsupported/overhanging surfaces). Part orientation should be considered as part of the design process to ensure final material properties meet part requirements.

7.3 Dimensional Control.

Different AM processes/parameter combinations provide different dimensional control capabilities. The capability of the selected AM process/parameter combination to create essential part features, such as minimum and maximum wall thickness and fillet radii, should be considered during the design process. Localized heat input associated with AM processes used with metallic materials can result in the creation of significant residual stress in the fabricated part. These stresses and potential post processing warpage should be accounted for in the design process and associated mechanical property analysis. If post-processing thermal cycles, such as stress relief thermal cycles or HIP cycles are employed, dimensional control for the final part should be demonstrated after all post-processing thermal cycles have been completed.

7.4 Surface Condition.

The surface conditions associated with AM processes can be significantly different from surface conditions produced by traditional subtractive manufacturing approaches.

7.4.1 Surface Finish.

The surface finish of an AM part can vary significantly depending on the selected AM modality, machine, machine parameters, feedstock material, and orientation of a given surface. For this reason, the surface finish can vary significantly as a function of location on a part. Surface finish values should be determined during the part development process and reflected in the design values.

7.4.2 Feature Related Surface Conditions.

Due to the layer-by-layer addition of material that occurs with AM processes, varying surface conditions can be created during the formation of features, such as unsupported arches, overhanging surfaces, and self-supporting structures (see Figure 4 in this AC).

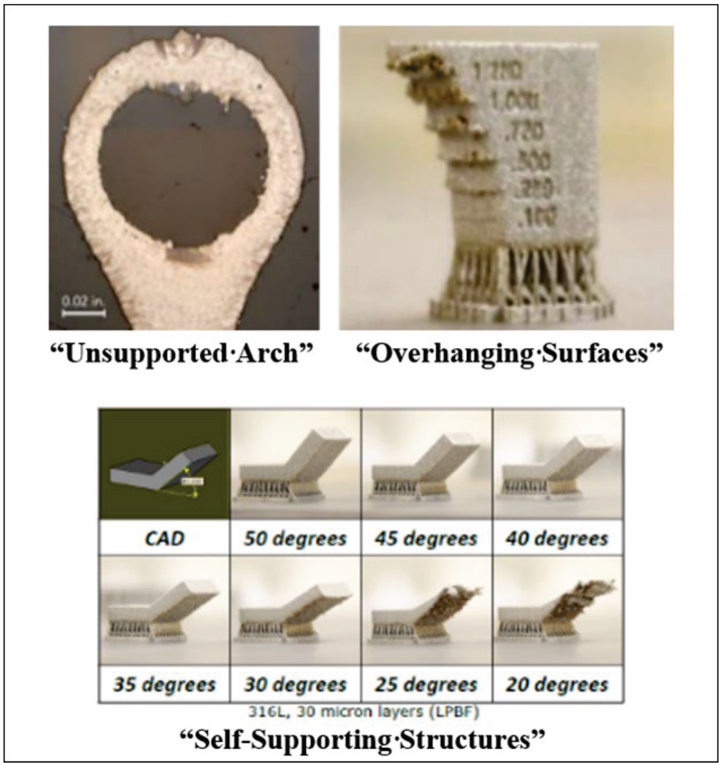

Figure 4. Unique Feature Related Surface Conditions

7.4.3 Surface Condition Impact – Mechanical Properties.

Mechanical properties that are sensitive to surface condition will require detailed characterization to establish mechanical property debits associated with the surface condition as described in paragraph 6.4.6.2.

7.4.4 Surface Condition Impact – Inspectability Limits.

The surface condition associated with AM processes can also impact inspectability limits associated with conventional NDI processes. Depending on the surface condition resulting from selected processing, part surfaces may require NDI process development. The requirement is to demonstrate adequate resolution to detect the specified defect size (see paragraph 10.6).

7.4.5 Surface Finishing Considerations.

Traditional surface finishing approaches, including non-conventional methods, can be applied to both external and internal surfaces of AM parts. However, complex internal geometries associated with some AM parts may not be accessible. Parts designed to operate with the as-fabricated surface conditions should include associated mechanical property debits where such surface conditions exist on the part. See figure 3 in this AC.

7.4.6 Protective Coating Considerations.

Standard protective coatings, such as coatings used to address corrosion, oxidation, or erosion can typically be applied to both external and internal surfaces of AM parts that have been subjected to surface finishing treatments. Application of coatings on as-fabricated internal passages may be difficult due to as-fabricated surface conditions.

7.5 Support Structures.

Support structures can be used to minimize the occurrence of unsupported arches and overhanging surfaces. Additionally, support structures can be used to help transfer heat away from local areas as new layers are added and to help retain the part's shape. For an example of the use of support structures during the AM PBF build process, see Figure 5.

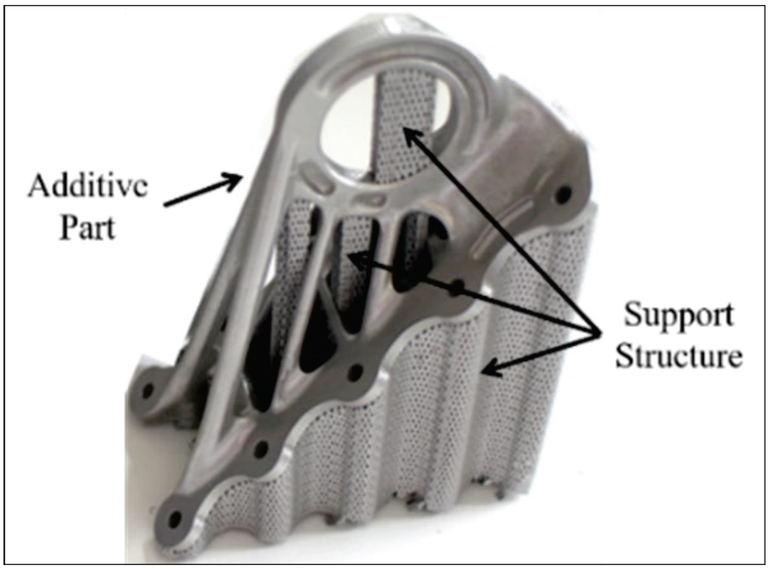

Figure 5. Example of Support Structures Used with Additive Parts

Note: There are drawbacks to the use of support structures during AM. Supports formed inside parts cannot be removed after part fabrication. Removal of supports from external surfaces can result in the creation of local stress concentrations that can have deleterious effects on mechanical properties.

7.6 Powder Removal.

When PBF AM processes are used to produce parts with internal features, unfused powder can become trapped inside the part during the build process. Part designs and part orientation during the build process should be defined such that removal of loose powder can be accomplished. Effective powder removal procedures should be identified. For cases where powder removal may not be accomplished, functional tests should be performed to verify that any potential residual powder does not interfere with intended function of the part.

Note: Failure to remove loose powder before application of post-processing thermal cycles can result in sintering of loose powder to the parts internal surfaces such that the loose powder can no longer be removed.

8 MATERIAL AND FABRICATION.

8.1 Material and Process Control.

Depending on the selected PBF AM process, more than 100 parameters may be used to control the fusion process. Examples of key process variables requiring control include directed energy source power, scan speeds, layer thickness, fill patterns, chamber atmosphere, chamber temperature, feedstock material, and reuse of feedstock material. Process parameters that have a direct influence on the chemical, physical, metallurgical, dimensional, or mechanical properties of the final AM part should be identified, defined as key process variables, and carefully controlled. Process validation is the system that defines how to identify significant process parameters, identifies their limits, and determines if they have a deleterious effect on the defined requirements. Specifications covering AM feedstock material, including reuse of feedstock material, material processing, and fabrication procedures should be established in conjunction with process validation to ensure a basis for fabricating reproducible and reliable material.

8.1.1 Feedstock Material Specification.

8.1.1.1 For powder-based AM processes, control of the powder feedstock is essential to a quality fusion process. The key characteristics of the powder, such as powder chemistry, particle shape, particle size distribution (including size limits), cleanliness, and powder flow characteristics should be identified and defined in the feedstock specification along with acceptance testing requirements. The feedstock specification should also identify the powder production method.

8.1.1.2 Specifications for feedstock materials limit the variation in composition, trace elements, impurities, and other characteristics that are inherent to the feedstock material form based on material performance sensitivity studies. These specifications are required to ensure consistent material is being procured. Feedstock material specifications should also define batch acceptance testing or statistical process controls that ensure material properties do not drift over time. Material requirements identified in the feedstock specification are derived from process validation activities used to identify the key process variables that strongly correlate with the attributes required in the final AM parts.

8.1.2 Reuse of Feedstock Material.

8.1.2.1 If reuse or recycling of powder – including closed loop powder flow processes – is allowed, the applicant should show that reused powder continues to conform to the requirements of the feedstock material specification.

8.1.2.2 If blending of reused and virgin powder is allowed, the applicant should show how blending of reused powder is accomplished. Regardless of whether 100 percent reused powder or a blend of virgin and reused powder is used – including close loop powder flow processes – the applicant should define any limitations on powder reuse (e.g., number of build cycles, number of build hours, hours in the machine, and powder oxygen level). Finally, the applicant should show that final part properties, including material properties, continue to conform to all design requirements at the limit of reuse (see paragraph 6 in this AC). Reuse of powder should be controlled by the specification.

8.1.3 Process Validation.

Process validation is used to ensure that key process variables which strongly correlate with the attributes required in the final AM parts, such as mechanical, physical, metallurgical, or chemical properties, are appropriately defined and frozen such that process requalification is required if one or more of these key process variables is changed. Before freezing these key process variables, parametric studies (i.e., process validation) should be completed to define their critical tolerance values in the process specifications. Process specifications should address:

- Shop and equipment operating procedures.
- Power level verification.
- Software control.
- Build interruptions and machine restarts.
- Environmental controls.
- Contamination control plan.
- Powder handling and reuse requirements.
- Quality assurance requirements.

8.1.4 Part Material Specifications and Engineering Drawings.

Part material specifications and engineering drawings establish the acceptance requirements for parts fabricated by PBF AM. These documents include any required post-AM processing operations and should ensure that variation in strength and other properties meet design properties consistent with the design intent. Material anomalies, such as porosity and inclusions that are permitted by the material specifications, should be substantiated by test evidence at the specimen or part level. These specifications should include a process for confirming that material properties continue to meet assumptions reflected in the design data via periodic specimen or part level testing. Part material specifications, when combined with engineering drawings, should address chemistry, mechanical properties, microstructure, porosity, surface finish, thermal processing, and quality assurance. These documents should also address any required post-AM processing operations. Additionally, the part material specifications should address certification of conformance to the material specification for the feedstock material including such features as input powder chemistry, number of powder re-uses, process specifications, and attributes that link the AM part back to the material used to develop the design curves associated with the material specification.

9 POST BUILD PROCESSING.

9.1 Post Build Operations.

After completion of the build cycle, AM parts will be subjected to one or more post build operations. The sequence and specifics of these operations may affect the final part microstructure, material characteristics, residual stress, and dimensional control. Post build operations, including the sequence of these operations, should be documented in a control plan. Examples of post build operations include removing AM parts from the build platform, removing support structure, removing residual powder from the AM parts, subjecting AM parts to one or more thermal cycles, and use of surface enhancement treatments to address surface condition.

9.2 Residual Powder Removal.

If applicable, residual powder should be removed from AM parts. Steps should also be included to confirm that all residual powder has been removed when required.

9.3 Residual Stress.

The multiple localized melting and re-solidification cycles associated with AM processes can result in significant residual stress being developed in AM parts. As a result, part distortion can occur during the application of post build thermal processes and engine operation. The method(s) for addressing residual stress in AM parts associated with the build process should be accounted for in the design process.

9.4 Removal from the Build Platform.

The method for removing parts from the build platform should be defined. The sequence in which parts will be removed may also need to be defined.

9.5 Removal of Support Structures.

The method(s) for removing support structures from the AM part should be defined in the part material specification or on the engineering drawing if removal is required. The sequence in which support structures will be removed may also need to be defined.

9.6 Thermal Processing.

It is expected that AM parts will require thermal processing operations to evolve the as-built microstructure into a final form, yielding proper and predictable material performance. If thermal cycles are used to improve material microstructure, such as to reduce anisotropy and/or improve homogeneity, each thermal cycle should be sufficiently controlled to ensure repeatable and reliable results. Any specific requirements for final microstructure attributes, such as an acceptable level of anisotropy and the method used for confirming acceptable microstructure attributes, should be defined in the part material specification or on the engineering drawing.

9.7 Hot Isostatic Pressing (HIP).

If AM parts are subjected to HIP, the process parameters for this operation should be defined. Any specific requirements for final microstructure attributes and the method used for confirming acceptable microstructure attributes should also be defined.

9.8 Surface Enhancements.

To address surface roughness associated with "as produced" AM parts surface enhancement treatments may be applied. The type of surface enhancement(s) applied to parts should be defined in the part material specification or on the engineering drawing.

9.9 Environmentally Protective Coatings.

Environmentally protective coatings may be applied to AM parts. The type of protective coating applied to the parts should be defined, and the potential effect on substrate material properties should be understood.

10 INSPECTION METHODS.

10.1 Inspection Method Considerations.

While AM parts may present unique inspection challenges compared to cast and wrought products, from an NDI perspective they are finished parts that should be inspected. The NDI development and verification processes used for cast and wrought products can be applied to the parts produced by these new manufacturing processes. Additionally, radiographic requirements specified in industry standard welding specifications may also be used.

10.2 Relationship to the NDI Development for Cast and Wrought Products.

The physics of the layered AM process produces different types of material anomalies than those produced in traditional cast and wrought products. The layer-by-layer deposition approach used in the AM processes may produce anomalies that do not possess significant height in the build direction. Planar anomalies, such as lack of fusion, tend to form along the build plane and can be only one to two layers thick. In addition, as-built surfaces that are not well supported during the build process can be rough and mask the presence of surface anomalies. While all the inspection processes typically used for cast and wrought products, such as radiography, dye penetrant, eddy current (EC), or ultrasonic testing (UT) are applicable to AM parts, they may need to be applied in new or combined ways to detect anomalies produced by AM processes.

10.3 Role of Inspection in AM Part Quality.

NDI should not be viewed in isolation when developing a plan to ensure the integrity of AM parts. NDI should be viewed as one option to ensure part integrity along with process validation, process monitoring, proof testing, periodic destructive evaluation, and other established quality control methods. Inspection should be integrated with these other methods in a complementary way to ensure part quality.

10.4 Identification of NDI Criteria.

As with any traditional part, the first step in developing an inspection technique is to understand the inspection requirements for the part. As part of the materials characterization process outlined in paragraph 6, material anomalies intrinsic to the selected AM processing parameters, material system, and part design should be identified. Examples of possible material anomalies include porosity, lack of fusion, excessive surface roughness, and inclusions. In addition to the type of anomalies produced by the AM process, the maximum size of those anomalies that the design can allow should be specified. Identification of areas with different acceptance criterion (for example, proximity of allowable defects) is acceptable similar to how castings are treated, provided the applicant can demonstrate that such an approach is consistent with engineering and design requirements. NDI experts can select and validate the appropriate NDI technique(s) with this information.

10.5 Placement of NDI within the Manufacturing Process.

Using the inspection criteria described in paragraph 10.4, it is important to locate the inspection correctly within the sequence of operations for the part. For example, if a part goes through a HIP operation to eliminate porosity, it may not be appropriate to inspect for porosity before the HIP operation. Inspection prior to HIP is acceptable but may produce unallowable indications that will be healed in a subsequent operation. Similarly, if machining damage may occur, the inspection for that damage should occur after all machining operations are complete.

10.6 Selection of NDI Techniques.

Once the type of anomalies, allowable sizes for those anomalies, and the placement of NDI within the manufacturing process sequence are established, NDI techniques can be evaluated and selected. To evaluate NDI techniques, components with examples of the anomalies, or artificial features that are considered representative of the anomalies, need to be manufactured. Due to the nature of the AM process, parameters used to produce these components should be as closely aligned to the final manufacturing process parameters as possible. Regardless of the NDI process(s) selected, acceptance criteria should be established and verified.

10.6.1 Radiographic Testing (RT) and Computed Tomography (CT).

RT and CT process capabilities are dependent on part geometry. One of the advantages of AM processes is rapid design iteration by eliminating the need to create dies or tooling. If CT capability is determined too early in the design process, changes in part geometry by the final design iteration may change capability in critical areas.

10.6.2 Ultrasonic Testing (UT) and Penetrant Testing (PT).

The capability of UT and PT are influenced by surface condition. The surface condition of AM parts can change significantly based on build parameters and support structure placement. Inspection capability should be assessed on samples representative of the final manufacturing process.

10.7 Inspection of Rough Surfaces.

10.7.1 As discussed in paragraph 7.4, the as-built surface condition of AM parts differs from those produced by traditional manufacturing methods. The surfaces, in general, are rougher than those produced by casting or wrought processes and have more variation. The condition of the as-built surfaces requiring inspection should be considered when selecting the NDI method(s) to be used to evaluate parts. An impact study should be conducted on specimens that are representative of the final as-built surfaces for the component to ensure adequate capability to detect conditions of concern.

10.7.2 For surfaces where NDI capability is reduced due to surface roughness, additional manufacturing steps should be considered to improve surface conditions. Surface finishing processes, typically used with cast and wrought products, may be used to improve the inspectability of surfaces. Improving surface finish is preferred to selecting an NDI method whose capability is not impacted by surface roughness but is not as capable of finding the specified anomaly types.

10.8 Inspection of Complex Geometries.

AM process can produce part geometries that are not possible using traditional manufacturing methods. While these new geometries provide great benefits for cost and performance, they can create challenges for traditional NDI approaches. New complex geometries will require new inspection approaches, including the combination of multiple NDI methods and new or emerging NDI methods, such as laser ultrasonic testing (LUT) or CT.

10.9 Inspection of Internal Features.

AM parts often have internal features that need to be inspected, but access to these surfaces is partially or completely obstructed. As a result, traditional dimensional and NDI methods may not be sufficient.

10.9.1 CT Inspection Systems.

CT is one inspection method currently approved for the inspection of internal features that cannot be directly accessed. Currently, there are four different categories of CT inspection systems:

- Nanofocus (140-200 KeV).
- Microfocus (200-450 KeV).
- Mini-focus (300-600 KeV).
- Industrial (1000-9000 KeV).

The type of CT system to use depends on the size and density of the part to inspect, the size of the feature(s) to be measured, and anomalies to detect. In general, higher-powered systems have more penetrating power for large or dense parts but produce images with lower resolution.

Note: Kiloelectron volt (KeV) is the power of the x-ray system measured in 1000s (K) of electron volts (eV).

11 PROCESS QUALIFICATION.

11.1 Process Qualification Considerations.

The fundamental goal of fusion process control is to consistently achieve consolidation of the feedstock material to the greatest extent possible without the presence of fusion-related defects. The process parameters specified to control the fusion process are set to achieve the desired material density, geometric detail, microstructure, surface condition, and other fusion-related characteristics in the as-built structure. The AM process should be properly controlled to produce stable and reproducible dimensions, properties, and quality.

11.2 Process Validation.

Process validation is the methodology used to verify that a component manufactured to a specific process, process sequence, and drawing requirements meets the design intent. Process validation requirements include, but are not limited to, first article inspections, destructive evaluation of parts, NDI evaluations, metallurgical examinations, and chemistry and mechanical property testing. Process validation should also address potential feedstock variability, machine variability, and post processing variability. Assessment of machine variability should include variability within the build volume, run-to-run variability, and variability between machines.

11.3 **Qualifying a Fixed Process.**

Process validation is necessary to assure that all physical, chemical, and metallurgical material characteristics are satisfied, and to ensure that manufacturing anomalies are not introduced by the process. Process characteristics that have a direct influence on the final AM part mechanical properties and physical attributes are identified as key process variables that should be defined and carefully controlled in a specification and/or technical plan. Review and approval of the overall process specification and quality control plan should involve engineering, manufacturing, and quality functions. The process specification and/or technical plan should require process requalification if one or more of the key process variables is changed.

11.4 **Machine Qualification.**

Qualification runs should be accomplished in accordance with the approved specification and/or technical plan to verify that the fabricated parts have the material properties assumed in the design data for the part.

11.4.1 <u>Part and Specimen Evaluation.</u>

Both destructive and non-destructive evaluation of parts and specimens can be used to support initial and ongoing process validation. Destructive evaluation is necessary for validation of certain engineering or quality characteristics, such as physical, chemical, and metallurgical aspects that are not inspectable by conventional NDI techniques. The selected combination of destructive and non-destructive evaluation of parts and specimens should demonstrate that all engineering requirements are achieved with the defined process parameters. Evaluation parts and specimens should be produced with feedstock material reflecting the approved feedstock material specification criteria including reused powder, if applicable, and be representative of the variability introduced by the manufacturing process used to fabricate production parts. Parts selected for evaluation should also be representative of all build positions.

11.4.2 <u>Part and Specimen Evaluation Plan.</u>

The part and specimen evaluation plan should address ongoing process validation through a combination of destructive and non-destructive evaluation of parts and specimens. A periodic destructive evaluation sampling plan should be established that ensures confirmation that engineering requirements continue to be achieved with the defined process parameters. The sampling frequency and number of parts and specimens sampled should be established based on demonstrated statistical process control and should – over time – address all build positions. Periodic mechanical property validation through testing of parts or directly produced specimens should also be incorporated into the process validation plan.

11.4.3 Inspection Data.

NDI plus destructive evaluation of parts from process validation demonstration builds should be performed consistent with the inspection method considerations provided in paragraph 10. This evaluation should demonstrate that any anomalies present in parts are acceptable to design requirements. NDI tests for process validation demonstration should be performed at the same point in the overall part manufacturing sequence as defined in the process specification and/or technical plan.

11.4.4 Specimen Testing.

Specimen testing from process validation demonstration builds should be performed consistent with the test program approach described in paragraph 6. This testing should confirm that material properties in the fabricated parts match the material properties assumed in the part design data including required post build processes.

11.4.5 Traceability.

Due to the batch nature of AM processes, development of a system for part traceability is highly recommended. Retention of records such as powder heat, lot and condition (for example, virgin or recycle count), machine serial number, build number, and part location in the build chamber are recommended for each part produced.

11.5 Qualification of Multiple AM Machines.

When multiple AM machines will be used to produce parts using identical parameters, a separate process validation should be executed for each machine.

11.6 Changes to Key Process Variables.

Changes to key process variables should not be introduced to the fixed process unless additional qualification, including testing of differences, is completed. All changes to key process variables should be validated for each machine on which they are introduced.

12 SUGGESTIONS FOR IMPROVING THIS AC.

If you have suggestions for improving this AC, you may use the Advisory Circular Feedback Form at the end of this AC.

Digitally signed by VICTOR W WICKLUND
Date: 2023.06.23 16:43:07 -04'00'

Victor Wicklund
Acting Director, Policy & Standards Division
Aircraft Certification Service

OMB Control Number: 2120-0746
Expiration Date: 11/30/2024

Advisory Circular Feedback Form

Paperwork Reduction Act Burden Statement: A federal agency may not conduct or sponsor, and a person is not required to respond to, nor shall a person be subject to a penalty for failure to comply with a collection of information subject to the requirements of the Paperwork Reduction Act unless that collection of information displays a currently valid OMB Control Number. The OMB Control Number for this information collection is 2120-0746. Public reporting for this collection of information is estimated to be approximately 20 minutes per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, completing and reviewing the collection of information.
All responses to this collection of information are voluntary FAA Order 1320.46D Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to: Information Collection Clearance Officer, Barbara Hall, 800 Independence Ave, Washington, D.C. 20590.

If you find an error in this AC, have recommendations for improving it, or have suggestions for new items/subjects to be added, you may let us know by (1) emailing this form to (__________________) or (2) faxing it to the attention of the LOB/SO (___________________).

Subject:____________________________ Date: ___________________

Please mark all appropriate line items:

☐ An error (procedural or typographical) has been noted in paragraph__________________on page_________________________.

☐ Recommend paragraph___________on page_______________be changed as follows:

☐ In a future change to this AC, please cover the following subject:
(Briefly describe what you want added.)

☐ Other comments:

☐ I would like to discuss the above. Please contact me.

Submitted by:_________________________________Date: _______________________