Job Aid for Evaluating Additive Manufacturing at an MRO

December 2018

Table of Contents

Definitions.

Additive Manufacturing (AM): Describes the process of joining materials to make objects from three-dimensional (3-D) model data using a layer-upon-layer technique/method, as opposed to subtractive manufacturing methodologies.

Anisotropy: Exhibiting properties with different values when measured in different directions.

Build: A complete operation of the powder build fusion process to create objects, including parts as defined in the 3-D build model. It is common for multiple parts, witness specimens, etc., to be produced in a single build.

Build Area: The area of the build platform where the fusion process is qualified to produce parts. This area may be less than the full capability of the powder bed fusion (PBF) machine.

Build Chamber: The volume in which parts may be produced in the powder bed. This volume is defined as the build platform area and maximum height of the build platform.

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 platform: A flat plate upon which the parts are built.

Design Allowables: Material properties that have been determined from test data and selected to assure a high degree of confidence in the integrity of the completed part. These values are typically adjusted to account for anomalies associated with the selected fabrication process.

Fatigue Strength: Alternating stress that can be sustained by a part for a given number of loading cycles. This material property varies with the level of mean stress and is temperature and strain rate dependent.

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

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

Mechanical Properties: Tensile properties, elasticity, creep and stress rupture properties, high-cycle fatigue, and low-cycle fatigue.

Metallurgical Properties: Chemical composition, material form, microstructure, hardness, and the influence of surface coatings or treatments.

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

Powder Blending: The process of combining powders of the same nominal composition originating from more than one heat or lot of powder.

Powder Heat: The product of one vacuum melt cycle and gas atomization run.

Process Specification: The applicants' process specification that controls the manufacturing of an AM part, including the PBF machine process parameter settings. In some cases, the parameter values may be defined in a separate document (e.g., Technical Plan or Process Control Document). This document is different from an FAA-approved repair specification (RS) used by a 14 CFR part 145 repair station.

Powder Recycling (or reuse): The use of powder in a build that has been exposed to one or more previous builds in a PBF machine.

Significant Process: A process that, if changed, could affect physical, mechanical, metallurgical, or chemical properties.

Support Structure: Is built with the part to provide dimensional stability to overhung surfaces and to transfer heat away from the part as new layers are added.

Process Validation: A manufacturing/quality/engineering system for process control of complex safety significant parts.

Introduction.

A. This job aid is a tool to assist aviation safety inspectors (ASI) in evaluating the use of AM by a Maintenance Repair Organization (MRO) that fabricates replacement parts in accordance with 14 CFR part 21, § 21.9(a)(6) owner-produced parts. The eight elements of this job aid consist of a systematic review of AM considerations that can be utilized in evaluating an AM process used at an MRO, regardless of its size and part complexity or category. Refer to FAA Order 8900.1, Volume 6, Chapter 11, Section 29, Inspect the Use of AM in the Maintenance and Repair of Aviation Products and Articles (Parts 91, 121, 135, and 145), for specific information concerning the use of AM to fabricate complete repair parts.

B. This job aid is organized to assist the FAA ASIs in performing a systematic evaluation of specific elements of an AM process being evaluated at an MRO that are critical to the successful use of this technology, such as: training, equipment, materials, technical data, qualified personnel, etc., and to ensure that parts fabricated under § 21.9(a)(6) use an AM process that complies with the 14 CFR part 43, § 43.13 requirements of being equal to their original or properly altered condition.

C. Based on this evaluation, the ASI should be able to determine whether or not further in-depth evaluations are needed.

> **NOTE:** A negative answer to a question does not necessarily imply that a process is out of conformity. This is not a pass/fail checklist but a means to gain an understanding of the certificate holder's program and the AM technology to be used, and determine if additional subject matter expertise is needed to assist both you and the certificate holder.
>
> **NOTE:** This job aid is intended to be a living document to be enhanced as the technology advances and questions/concerns are raised by you, the ASI.

Organization of This Job Aid.

A. This job aid includes a section to record pertinent information about the repair facility, followed by questions to evaluate each of the elements. Not all the questions in the elements are applicable to every repair facility. Each element has an area for remarks associated with that question. For example, the repair technical data section includes specific questions used to evaluate the validity of the data used for repairs and the application of those standards within the repair facility.

B. The answers to the questions in each element will assist the ASI in evaluating what level of part complexity/category the MRO can successfully fabricate in accordance with § 21.9 and § 43.13.

Guidance.

- Order 8900.1 Volume 6, Chapter 11, Section 29, Inspect the Use of Additive Manufacturing in the Maintenance and Repair of Aviation Products (Parts 91, 121, 135, and 145).
- AC 43-18, Fabrication of Aircraft Parts by Maintenance Personnel.
- Category Parts List (CPL) information referred to in AC 43-18 resides in FAA Order 8120.23, Certificate Management of Production Approval Holders (current revision with the actual list residing in a Manufacturing Best Practices document at http://www.faa.gov/aircraft/air_cert/production_approvals/mfg_best_practice/).

Section A: General Repair Station Information

Repair Facility/Location/Ratings:

Date Started:_____Date Completed_____

Evaluating Inspector (ASI)	Repair Station Representative	Title

Employees Trained in Additive Manufacturing (AM)

Certificated Mechanics	
Non-Certificated Mechanics	
Repairman	
Total Employees	

Identify AM Technology evaluated.

AM Technology (Laser Powder Bed (LPD), Direct Energy Deposition (DED) etc.)	Material Type (Metal or Polymer) & Form (Powder or Wire)	Part Number	Part Category	FAA Approved Repair Specification or Data Acceptable to the Administrator Yes/No include number
Note: A clear understanding of AM Technology and materials being used will ensure a thorough evaluation of the process and airworthiness if repair parts being produced. **Note:** If the MRO is using multiple AM technologies evaluate each one separately **Note:** Refer to Guidance section of this job aid for information on Part Category				

Observations and Comments

_____

_____

_____

Section B: Evaluation

Table 1: Training Programs

Does the repair facility have a training program? Does the training program cover all the employees, involved in Additive Manufacturing (AM)?

Question	YES/NO	N/A	REMARKS
Does the organization have an AM training program that supports the AM technology identified in Section A that is part of their approved training program?			
Does the facility have detailed job descriptions that define the roles and responsibilities of each employee involved with the AM process used by the facility?			
Does the training curriculum address all AM job functions defined by the organization to include initial and recurrent training?			
Does the training curriculum include all AM industry, FAA Regulations, FAA AM Policy, and organizational standards, specifications, and qualification procedures and require trainees to demonstrate knowledge of the specific AM technologies identified in Section A?			
Does the training include understanding and demonstration of common defects, build errors, and risk mitigation associated with the AM technology/process?			
Does the training include specific AM machine operator qualification and include process steps such as setup, loading, post processing, cleaning, powder handling, etc.?			
Does the training program address the significant process control elements?			
Does the training program address the inspection methods, techniques, practices, equipment, and tools?			
Is AM-specific software training conducted that includes process revalidation following a major revision?			
Are the facility's employees who service and maintain AM equipment trained or certified to complete work performed on all models of AM equipment used?			
Does AM training address specific contamination and prevention related to AM materials such as powders, gasses, etc.?			
Does the training curriculum address the FAA-approved repair specifications (RS) used at the facility to include post-build part conformity and regulatory validation?			

Question	YES/NO	N/A	REMARKS
Are personnel that perform inspections of AM produced parts to include nondestructive inspection (NDI) personnel trained on unique aspects of inspecting AM-produced parts?			
Does the AM training include all management personnel who oversee AM software and production employees?			

Table 2: Facilities

This involves the general physical condition of the facility, e.g., housekeeping, storage, safety, consumable management. Does the repair facility have the necessary space conditions to perform AM?

Question	YES/NO	N/A	REMARKS
Has the facility identified the unique environmental requirements for the AM technology identified in Section A?			
Are environmental conditions controlled (e.g., cleanliness, relative humidity, air temperature, etc., per specification and AM machine manufacture requirements) at the facility?			
Are the temperature and humidity measuring locations, if required, properly located and calibrated per specification requirements?			
Does the facility provide necessary protection of equipment, materials, and post build articles?			
Does the facility have and utilize procedures to prevent cross-contamination so that AM machines are isolated from other processes? (e.g., welding, grinding, and machining)			
Does the facility have sufficient controls to meet the environmental requirements for the storage of raw materials required by the material manufacturer?			

Table 3: Technical Data

Does the repair facility have procedures and processes for repairs? Technical data for AM typically includes drawings, FAA-approved RS, program files for the machines, fixed planning, etc.

Question	YES/NO	N/A	REMARKS
Does the company use data acceptable to the Administrator based on fabricated replacement part criticality (e.g., safety critical, durability critical, non-critical)?			
Does the company make available current industry AM Standards and Specifications? This can be in the form of hard copies or electronic.			
Does the company have a detailed operations procedures manual for the AM equipment in use, and is it current?			
Does the repair facility have an engineering department (or contract with a third-party engineering firm) to develop independent repair data?			
Does the FAA-approved RS or other data acceptable to the Administrator identify the significant AM process control parameters and define how to monitor these?			
Does the approved technical documentation describe how to validate the post-build item and document § 43.13 part equivalency including, if needed, metallurgical evaluation?			
Does the repair facility make AM technical data available to all personnel involved in the AM technology identified in Section A?			
Does the facility have a documented process for making major/minor repair classifications of AM repairs?			
Does the MRO outsource AM? If so, do they provide all technical documentation and audit to ensure compliance?			
Does the MRO using outsourced AM provide a current list of all outsourced AM to the CH?			
Does the MRO have an audit plan for outsourced 3rd party AM and provide the data to the part 121 CH?			
Does the CH using the MRO outsourced AM maintain oversight of the outsourced AM with audits?			

Table 4: Material Handling

The purpose of this section is to evaluate the repair facility using an AM process to ensure that they have documented procedures for the proper handling of all materials: powders, gasses, build plates, re-coater blades, etc., that are used in the AM technology identified in Section A, and that these procedures are effective in managing any unique requirements of AM materials.

Question	YES/NO	N/A	REMARKS
Does the facility have designated storage areas for raw materials that meet the AM specification material storage requirements?			
Are facility raw material records maintained that demonstrate traceability of a specified repair build cycle to the specific material lot used?			
Does the facility have a documented material testing/validation process as part of the initial receiving inspection for new materials?			
Does the facility have a documented procedure for reusing and blending of certain materials?			
Is there a documented procedure that validates material humidity and temperature requirements throughout storage life?			
Are appropriate measures taken to prevent material contamination during handling and storage?			
If gasses are used in the AM machines, are they the proper type and grade in accordance with specification requirements?			
Are the same machines used for multiple materials? If so, are controls in place to prevent cross contamination?			
Are procedures in place to control reused material (such as powdered metal), including tracking the number of cycles on a batch, humidity, out life, etc., in accordance with applicable specification limits?			
Does the organization have a procedure to dispose of unusable materials (contaminated/exceeded maximum reuse cycles) that ensures they are not reintroduced into the supply chain?			
Does the facility have the type and grade of material called out in the approved repair specification for the AM technology in use?			

Table 5: Equipment, Tooling, and Calibration

The purpose of this section is to highlight unique areas of oversight that may exist with AM equipment, tooling, and calibration. Depending on the AM equipment used and the equipment supporting these methods, specific and possibly unique equipment maintenance and calibration considerations may need to be defined, monitored, and controlled. It's important to note that periodic maintenance and calibration requirements may differ depending on individual equipment manufacturer's recommendations.

Question	YES/NO	N/A	REMARKS
Does the AM equipment used by the facility require periodic calibration?			
Are the AM machines and other required tooling related to material handling and testing of samples listed in the calibration/certification system?			
Do the facilities procedures require the validation of calibration currency of AM equipment before each use?			
Is there a documented maintenance schedule for AM equipment that includes a checklist of activities, instructions to perform each activity, and the frequency by which that activity must be completed? (AM machines require periodic cleaning and alignment).			
Are there defined allowables for all AM equipment?			
Are there methods in place to assure all equipment is within tolerances during the entire build cycle for each part build?			

Table 6: Software Controls

There are significant process control characteristics that are partially or completely controlled by software or firmware. The programs for machines may have the capability for operators to select the number of parts on a build plate. Controls for some of the process control parameters such as chamber temperature and heat-up time may also be controlled by the operator or the software. The machine will usually have proprietary software that was developed by the machine manufacturer that may be subject to periodic revisions. Processes should be in place to control this and make sure appropriate evaluations are done to make sure updates don't introduce problems.

Categories of AM Software:

1. 3-D solid model of the part from a Computer-Assisted Design (CAD) program. (Type Design)
2. AM machine program used to build the part.
3. AM machine-operating software. This is proprietary to the machine manufacturer in most cases. Changes can introduce inadvertent changes to the process. This should be considered in the facilities procedures.
4. Files will typically be generated with a build that records the values of the significant process control parameters. These files may be used to as part of the part conforming process.

Question	YES/NO	N/A	REMARKS
Is there a process to identify changes to machine software to determine if the changes affect the fabrication of parts? Note: Any machine software revisions should be coordinated via the appropriate Aircraft Certification Office (ACO) or designee to evaluate potential impact to final printed part. Example: if a specific RS calls out a specific machine make/model with at specific software revision.			
Are changes validated appropriately before releasing them for use?			
Does the facility have software revision control procedures that are traceable to a particular build?			
If process disruption occurs (electrical outage, software failure, etc.) are there appropriate controls in place?			
If a restart after process disruption is allowed, are there appropriate controls in place to evaluate impact to the final part?			
Does the production software include a build quality report, and is it used for process control?			
Does the AM facility maintain and review a list of the most current revision dates of each software program revision prior to each production use of that software?			

Table 7: Validation and Monitoring

The purpose of this section is to evaluate if the process validation and monitoring used by the organization are sufficient to ensure repair parts produced by AM technology meet regulatory performance requirements and are airworthy. Process validation requirements may include, but are not limited to, part cutups, metallurgical examinations, manufacturing sequence sheets, first article inspections, chemistry, and dimensional and mechanical properties.

Question	YES/NO	N/A	REMARKS
Is there a documented process validation requirement to substantiate that the AM process and post-build processing are stable and repeatable to ensure that fabricated replacement parts are equal to the parts that they are replacing? (§ 21.9 and § 43.13).			
Does the AM process define the elements (machine parameters) that are frozen and require requalification if changed?			
Are the definitions for significant and insignificant process changes defined and documented?			
Does the organization have detailed documented procedures for evaluating and approving changes to repair specifications? Note: any change must be FAA approved.			
Are repair part conformity inspection requirements documented and defined? (This should include any specific or unique inspection requirements to include NDT including the need for a metallurgical evaluation.)			
Are significant process control parameters monitored?			
Are control limits established for significant process control parameters and easily identified?			
Is there a documented process of the action taken when process control parameters are exceeded?			
Are there procedures that address control of un-inspectable characteristics (things like internal grid structures and porosity)?			
In the event that a process exceedance occurs, does the facility have a procedure to determine why the exceedance occurred?			
Is the facility rejecting parts and rendering them unusable when a significant process control parameter exceeds its limit, and is it documented?			

Table 8: Metallurgical Lab Procedures

NOTE: The determination for metallurgical testing will be determined by the approving Designated Engineering Representative (DER) and ACO and spelled out in the FAA-approved Repair Specification (RS) or other approved data.

Unlike traditional subtractive manufacturing processes, AM validation procedures may require a metallurgical lab to validate characteristics that are un-inspectable. The following types of laboratory examination may be included in the FAA-approved RS as part of the part conformity and validation process for AM parts:

1. Tension or "Pull" test – the tension strength is the most obvious outcome of this test, but the yield stress and the percent elongation before failure are often more important characteristics.
2. Chemical analysis – testing parts to verify that the incoming material and final material meet specification requirements. Or in the case of material that is being reused, to verify that contamination levels have not been exceeded.
3. Visual metallographic examination – the process of cutting and polishing samples cut from sacrificial parts, test coupons, or part features added for that purpose. Under a metallurgical microscope, the sample is examined to check the grain size, the directionality of the grain, to check for incomplete fusion, internal cracks, voids, inclusions, and other defects.
4. Fatigue testing – testing of parts that are critical for fatigue in service.
5. Fracture toughness – testing used to verify material resistance to cracks and defects.

All Post Build Operations must be documented in a control plan. Metallurgical properties of the AM part is very dependent on controlled post build processing.

Question	YES/NO	N/A	REMARKS
Does the FAA-approved RS require metallurgical testing? If "No" N/A this entire section.			
Is testing being conducted in accordance with national testing standards as required by the RS, typically ASTM?			
Are test specimens submitted to the lab properly identified for tracking?			
Are test specimens properly stored while they await testing?			
Are parts released prior to the results from lab testing? If so, how are they tracked if test results fail and are customers notified of part deficiency?			
Are testing standards objective, including pass-fail criteria?			

Question	YES/NO	N/A	REMARKS
Were tests performed in accordance with drawings and RS specifying the locations and orientations of samples taken for testing?			
Are the objective standards used in the lab under control? (Refer to § 21.137(f).)			
In the event that a specimen is found to not meet spec limits, is that AM machine and/or significant process control parameters evaluated for root cause and is action taken? (In some cases this may involve recertification of the AM machine.)			

Applicable References.

ASTM Standard F2792-12a, Standard Terminology for Additive Manufacturing Technologies.