Job Aid for Evaluating Additive Manufacturing Facilities and Processes

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Definitions

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

Build: A complete operation of the powder build fusion process to create objects, including parts as defined in the 3D 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 platform: A flat plate upon which the parts are built.

Powder bed fusion (PBF): An additive manufacturing (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).

Powder recycling (or reuse): The use of powder in a build that has been exposed to one or more previous builds in a powder bed fusion 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.

Note: ASTM F2792 contains additional definitions related to AM.

Preamble:

The introduction of Additive Manufacturing (AM) in the production of commercial aviation parts presents unique challenges. The term Additive Manufacturing itself does not describe one manufacturing method, but a wide range of methods, each with its own set of concerns and requirements. The job aid provided herein is not intended to be a comprehensive list of all the questions needing to be asked by the ASI. Instead, it's an initial reference. When faced with performing a product/process audit of an AM part, auditing a production approval holder's facility that utilizes AM, or as a member of a certification team, the ASI should consider the elements contained for preparing and completing such audits.

Introduction:

This job aid is a tool that aviation safety inspectors (ASI) can use to evaluate additive manufacturing of certificated aeronautical products. These elements comprise a systematic process that can be utilized in evaluating any additive manufacturing facility, to include PAH suppliers regardless of its size, complexity, and criticality

Additive manufacturing (AM) is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Materials can be polymers or metals. Heat is usually applied locally to melt the materials, resulting in thermally induced material transformations, as well as thermally induced stresses.

Role of the ASI in AM

The ASI's role in AM process validation differs from what you might see in a traditional metallic construction. As the process is designed and validated, the quality control procedures may have to be adapted and/or created to reflect the unique attributes of an AM process. In many cases, production surveillance procedures will be unique with respect to how an AM process is evaluated, hence this job aid. This is similar to composite construction in that the line between the ASI's role and the ASE's role is often blurred. When the ACO receives an application for an approval, they should notify responsible MIDO, and that ASI should participate in the certification activities. The conformity inspection plan, in the case of AM parts, should include verification and identification of the significant process control parameters. The ASI should be aware of the process validation plan, when required, and provide input to the ASE in the project planning. In addition, because the ASI is often in the facility and aware of the changes that are being made, they will frequently be the first to know of the incorporation of AM technologies to the product. For these reasons, it's especially critical that ASI's and ASE's work together as a team when dealing with AM.

This job aid also provides guidance for Aviation Safety Inspectors (ASI) responsible for the oversight of maintenance repair organizations (MRO) that perform maintenance, preventive maintenance, or alterations of aircraft, aircraft engines, propellers, or appliances using AM. This job aid is organized to ensure that an FAA ASI performs a systematic evaluation of specific elements of the AM process being evaluated that are critical to the successful use of this technology such as: training, equipment, materials, technical data, qualified personnel, etc. to ensure that the AM process achieves the 14 CFR 43.13 return to service requirements.

During a Risk-Based Resource Targeting (RBRT) Assessment and other risk assessment tools, the ASI should consider AM as a new and emerging technology when used.

Based on this evaluation, the ASI should be able to make a determination whether or not further in-depth evaluations are needed. A negative answer to a question does not necessarily imply that a process is out of conformity. These are simply questions that may be of use to the ASI.

ASI's should begin to use this job aid and provide feedback to an AMNT manufacturing focal when a PAH or one of their suppliers proposes to use an additive manufacturing process or if the ASI does not know if the answer is acceptable. Feedback from its use will play an important role in the ongoing development and improvement of this tool.

AM Manufacturing Focal Points

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Process Auditing

The manufacturing process is critical to AM and for producing intended results. For this reason, process auditing techniques are essential to a safe product. It is beyond the scope of this document to go into the details of process auditing techniques; however, many of the items specific to AM are reflected in this job aid. Particular attention should be given to the details in the process specification in effect and the implementation of those requirements at the facility.

Table 1: Training Programs

The purpose of this section is to evaluate the employee training provided by a manufacturing/repair facility involved in AM. Training should be specific to the AM technology utilized and equipment manufacturer requirements with emphasis on process functions such as operator, engineer, inspector, etc. Training should include prevailing industry and organization standards, qualification procedures, and equipment operation. The following job aid is not to be considered as an inclusive list of all elements of effective training for AM program.

	YES/NO	N/A	REMARKS
Does the organization have an AM training program? Identify specific AM technology being used, equipment type, & manufacturer in the remarks section, to the extent necessary for their job function.			
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 AM training curriculum address all job functions defined by the organization to include initial and recurrent training?			
Are AM personnel trained in industry and the organization's standards, specifications, and qualification procedures and able to demonstrate knowledge of the specific AM process/function being used?			
Does the training include understanding and demonstration of common defects, build errors, and likely causes of failure associated with the selected AM technology/process and associated mitigation techniques to ensure failures are avoided, contained, or minimized?			
Does the training include specific AM machine operation 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 including NDI used?			
Is AM specific software training conducted that also includes major revisions? (A major revision is one that changes a significant process element).			

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 FOD/contamination and prevention related to AM material, powders, gasses, etc.?			
Have individuals assigned to the Material Review Board (MRB) received AM training prior to making MRB dispositions of AM parts?			
Are personnel performing audits of AM suppliers properly trained and qualified in AM?			
Does the training include changes requiring additional approval and re-validation?			
Does the AM training curriculum provide instruction on capability and limitations of the AM equipment and process including: materials (alloys, properties, traceability), geometric features, surface finish, digital files, post-processing impacts, process parameters, and others as specified by the organization?			

Table 2: Facilities

The purpose of this section is to highlight unique areas of oversight that may exist with AM facilities. In the context of this job aid the term "facilities" is used to describe both the manufacturing organization as well as the physical aspects of the workstations. AM is extremely process dependent. There may be unique requirements that must be controlled to ensure quality of the final products.

	YES/NO	N/A	REMARKS
Has the facility identified the unique environmental requirements for all processes AM utilized?			
Are environmental conditions controlled (e.g., cleanness, relative humidity, air temperature, etc., within the specification requirements) at the facility?			
Are the temperature and humidity measuring locations representative of the material exposure and in accordance with specification requirements?			
Does the facility have suitable facilities for properly protecting articles during manufacturing process?			
Does the facility have and utilize procedures to prevent cross-contamination so that AM machines are isolated from other manufacturing processes?			
Does the facility have sufficient controls for the environmental conditions for storage and of raw materials?			

Table 3: Technical Data

Technical data for additive manufacturing typically includes drawings, specifications, program files for the machines, fixed planning, etc. Some of these documents, like the drawings and specifications, are clearly in the type design realm. While others, like the inspection requirements, are within the quality system. However, some types of data, like some of the manufacturing process planning, are somewhere in between the ASI and ASE's area of responsibility. For this reason, it is essential to communicate to avoid duplication of effort as well as possible oversight gaps.

	YES/NO	N/A	REMARKS
Does the AM design or process specification identify part classification (e.g., safety critical, durability critical, non-critical)? If so, what impact does that have on the requirements?			
Does the company clearly identify significant process control parameters? (If the significant process control parameters are not identified, you may want to contact the responsible ASE)			
Does the production process/software clearly reflect the design identification of significant process parameters?			
Has the company developed a frozen process that clearly identifies their significant process control parameters? (If the significant process control parameters are not identified on parts that are listed on the category parts list, you may want to contact the responsible ASE)			
When a fixed process is required (such as under 21.31), is that fixed process approved? When required based on the engineering requirements, fixed processes are considered part of the type design. The companies engineering department will need to approve the process and changes.			
When required based on part criticality, does the system have a way of identifying the significant process control parameters, and their associated measuring methods and limits?			
Have the ASI and ASE communicated and agreed on how fixed planning (process control) is approved and how changes are approved?			
Does the AM design identify process validation as a requirement for manufacturing process development, when appropriate?			

Table 4: Material Handling

The purpose of this section is to evaluate the production/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 process, and that these procedures are effective in managing any unique requirements of AM materials.

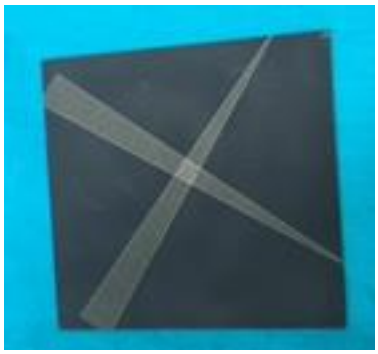
Typical Chamber in an AM Machine in a Laser Powder Bed Fusion Machine.

	YES/NO	N/A	REMARKS
Does the audited facility have designated storage areas for raw materials and does it meet the AM material storage requirements in the spec?			
Does the facility retain records traceable to the number of build cycles on a powder lot?			
Does the facility have document defining material testing processes? (Facilities may have additional documents over and above the engineering requirements that clarify the testing methods and the processing windows to improve the likelihood of building acceptable products with AM)			
Are batch acceptance testing procedures in place and in accordance with the spec requirements?			
Are materials removed from machines properly labeled and tracked as to status? (Ready for re-use, or awaiting reconditioning/testing)			
Is there a documented method that validates powder containers maintain atmosphere purity, humidity, and temperature throughout storage life? (Powder barrels, for example, often will come with a pressure gage to showing the vacuum and or inert gas is maintained)			

If blending is allowed of powders, (presents contamination risks) are there controls in place and are they followed? (Possibly additional testing required). Bending of powders is used either for chemical makeup reasons, but more commonly for re-use of power and will require the mixing of used powder with fresh batches.			
Is there a documented procedure to ensure that powder material, no longer sealed in its original container, is handled and stored in a controlled manner and environment that prevents contamination, oxygen, and moisture pickup?			
Is powder material handled and segregated in such a manner to prevent inadvertent co-mingling or cross-contamination?			
Are appropriate measures taken to prevent contamination during handling?			
Do purchasing instructions specify powder material specification, size, quality (e.g. flow characteristics, morphology, cleanliness), packaging (e.g. container type, sealed in inert gas) and identification requirements that are in compliance with stated requirements?			
If gasses are used in the AM machines are they the proper type and grade in accordance with spec requirements?			
Are the storage conditions for raw materials (such as powdered metal) controlled during transit in accordance with spec requirements?			
Are the same machines used for multiple materials? (Not recommended) If so, are controls in place to prevent cross contamination?			
Are procedures in place to control re-used 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 powders (contaminated/exceeded maximum reuse cycles) that ensures powders are not reintroduced into the supply chain?			

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 methods 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.



Example of a Laser Calibration Test Plate.

	YES/NO	N/A	REMARKS
Does the audited facility perform in-house calibration of its AM equipment and tools? (Checking table alignment, laser intensity, calibrating measuring equipment, verifying accuracy of temperature and humidity equipment, chamber pressure, beam diameter, beam tracking mechanism, position sensors, etc.)			
Are AM machines and other systems related to handling materials and the testing of samples listed in the calibration/certification system?			
Are AM machines qualified before being released for production use?			
Is there a documented maintenance schedule 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. Contamination can occur if good hygiene is not practiced).			
Is there a documented procedure for humidity and temperature control in the environment in which the machine and powder is located in the facility and are they continuously monitored and measured?			
Is the machine alignment/build plate alignment checked per spec requirements prior to a run?			

Is the build chamber volume periodically cleaned and seals maintained? Are the procedures effective in maintaining acceptable levels of cleanliness? (Looking for debris hanging from the chamber side walls and ceiling, leaky chamber seals).			

Table 6: Software Controls

To a greater extent than nearly all aircraft manufacturing activities at the current state of technology, software is an integral part of the process control for AM. The software comes in several categories. Some are controlled as part of the type design and some are controlled and developed under the quality system. Models developed by engineering defining the configuration of the final part are typically part of the type design and are, therefore, under the purview of the ASE. As the manufacturing plans are developed, the part specific programs are developed and the inspection software is developed and used. These procedures are either partially or completely the responsibility of the ASI.

In addition, there are other 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. 3D solid model of the part from a cad program. (Type Design)
2. AM machine program used to build the part. (If it is a frozen critical part, this is part of the type design. For other parts this may be controlled by the quality system).
3. AM machine operating software. This is proprietary to the machine manufacturer in most cases. The revision level is usually referred to in the frozen planning when applicable. 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 determine part acceptance. (Quality Records when used for acceptance)

	YES/NO	N/A	REMARKS
Is there a process to identify changes to software and determine if they are major or minor consistent with the standards in place?			
Are changes validated appropriately before releasing them for production use?			
When a part program is created for AM use, is the program validated in accordance with the specification requirements?			
Is there revision control on the programs?			

Are the significant process control parameters defined in the software identified, and are limits established for all of them? Typically, this will be by looking at the output files generated by the AM machine. (May be specification limits as well as upper and lower control limits)			
Are proper interlocks established for self-monitoring equipment to notify the operator in the event an anomaly is detected by the machine?			
Are best practices in place to use SPC to monitor significant process control characteristics, and apply corrective actions before drift occurs outside of specification tolerances? (The nature of the AM process is that most input parameters can be monitored, lending it to SPC.)			
Are procedures in place to ensure that if the part drawing (or data set) changes, the program is evaluated to make sure it is still correct?			
In the event that a process exceedance occurs, does the facility re-establish process capability?			
If restart after process disruption is allowed, are there appropriate controls in place?			
Are features added to the model for printing purposes (such as supports) clearly identified and post planning steps to remove them clearly communicated?			
In the event that a process exceedance occurs, does the facility re-establish process capability?			
If restart after process disruption is allowed, are there appropriate controls in place?			
If traveler test coupons are incorporated, are testing requirements clearly communicated and are their number, location, and orientations in compliance with specification requirements?			
Are operator instructions clearly documented for the production operator?			
Does the production software include a build quality report and is it used for process control.			
Are procedures in place of control of software to preclude revision of significant process control parameters without approval? (See AC 21-43 for further guidance)			

Table 7: Manufacturing Process Validation

The purpose of this section is to evaluate the process validation methodology used by the organization being audited to verify that a component is manufactured to a specific process, process sequence, drawing requirement and meets design intent. Process validation requirements may include, but are not limited to part cutups, metallurgical examinations, manufacturing sequence sheets, first article inspections, chemistry, dimensional, and mechanical properties.

All significant process changes to a frozen process plan that could impact the part design intent must undergo similar qualifications to the initial process validation prior to their introduction in the manufacturing process. Not all parts will require formal process validation, only when required by the criticality of the part. Source qualified parts are identified on a case-by-case basis by the manufacturer. Once a part is established to require source approval, manufacturing processes must be rigorously qualified and "frozen". Principal consideration during this qualification is given to vital engineering/quality characteristics, which are not inspectable by conventional Non-destructive Inspection Techniques. In general, these characteristics are physical, chemical, and metallurgical in nature and require destructive evaluation during initial qualification. All changes to these "frozen" manufacturing processes must undergo an approval process. It should be noted that frozen process parameters are not always defined by process specifications. In these circumstances, this information is contained in the approved manufacturer's fabrication technique as derived by the source approval. Significant Process Control Parameter limits are considered specification limits and are part of the type design and are non-conformities if exceeded.

	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 parts produced consistently meet design intent?			
Does the AM process define the elements (machine parameters) that are frozen and require requalification if changed?			
Does the AM process identify other process factors that should remain frozen such as environment, material quality, etc., that could affect the part design intent?			
Are documented procedures in place for internal auditing of the PAH/MRO validated AM processes to insure compliance with fixed/frozen AM manufacturing procedures?			
Are there documented controls that require approval of changes to a frozen process prior to introduction into the manufacturing environment and that demonstrate revision control is maintained?			
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 a frozen process plan?			
Are the first article inspection requirements documented and defined when a first article inspection is required?			
Do the documented process validation procedures define what a significant process parameter is?			

Table 8: Manufacturing Process Monitoring

Manufacturing parts through AM will typically involve some form of statistical process control. Significant process control parameters are selected and control limits are established so that the specifications limits are not exceeded. In most cases, applicants should have a Statistical Process Control (SPC) system in place to support AM. This will be similar to other types of process control monitoring, but with different parameters being monitored and the values will be different.

	YES/NO	N/A	REMARKS
Are significant process control parameters being monitored?			
Are control limits established for significant process control parameters so that specification limits are not exceeded?			
Is action taken when process control parameters are exceeded?			
Has the facility demonstrated that the AM process is capable and in control at the location being evaluated. *For example, the build layout should include witness coupons to be used as a record for the build. As defined by engineering, the coupons built may not need to be tested after every build once process control statistical confidence is established. The coupon geometry could be a generic specimen, a partial section of the part geometry, or a full part. This may include, but is not limited to, microstructure, grain size, chemistry, mechanical properties, and dimensional stability.*			
Are there procedures that address control of un-inspectable characteristics (Things like internal grid structures and porosity). (For characteristics that cannot be inspected, some sort of sampling plan, coupled with a process control plan based on process capability, would be necessary).			
In the event that a process exceedance occurs, does the facility re-establish process capability?			
Is the facility rejecting lots when Significant Process control parameter exceeds its limit?			
Does the approval holder have a procedure to print a new first article when certain triggering event occurs, like major maintenance, changes in manufacturing location, revision changes in process travelers etc.?			

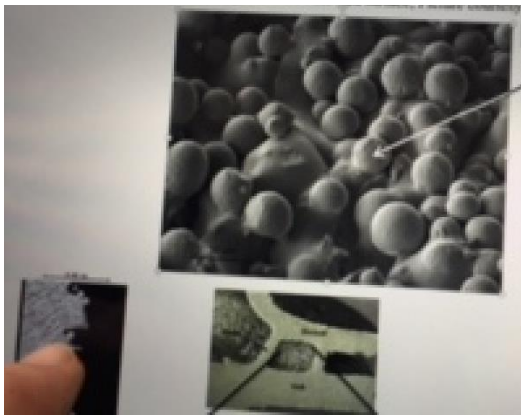
Table 9: Inspection and NDT

Defects and damage can occur during the production of AM parts. Various inspection techniques are available to detect defects such as porosity, inclusions, and contamination. These techniques vary widely from visual to computed tomography and are deployed to detect specific flaws. The effectiveness of an inspection application depends on the capabilities of the persons who perform or are responsible for the development and use of the inspection procedures. While the inspections will vary from facility to facility,

training, qualification of inspectors, validated written procedures, and calibration of equipment are all critical in assuring a quality product. While the techniques are very similar, the types of defects in AM parts differ from those in traditional subtractive parts. We would encourage facilities to use AM generated standards for defect detection.

	YES/NO	N/A	REMARKS
Are manuals and procedures available and used by the qualified personnel?			
Has the Design Approval Holder established likely AM defects to be detected using NDT and established appropriate thresholds?			
Are NDI requirements provided to the NDI inspection personnel by use of written procedures with accept/reject criteria and approved by a Level III in the method?			
Is there a procedure for calibrating inspection devices to certified standards made with AM representative defects?			
Are the calibration methods documented and accomplished at the beginning of each shift or prior to each use?			

Table 10: Metallurgical Lab Procedures



Example of the Surface of an AM part.

Unlike traditional subtractive manufacturing processes, additive manufacturing relies on the metallurgical lab to a much greater extent because other characteristics are un-inspectable. Lab testing is used to qualify new parts during the initial certification process, but is also a quality control method in production. Lab technicians should be familiar with the standards in place and the lab should have controls for machine alignment, load cell, and clip gage calibration, and training of the technicians. ASTM standards will usually control the necessary characteristics to assure a reliable test, but the acceptance or rejection limits will need to be established in the applicable specifications or drawings. The following types of laboratory examination may be included in the quality system for AM parts:

1. Tension or "Pull" tests, typically per ASTM E8, on samples cut from sacrificial parts, printed as part of a first article inspection for a new machine coming online, or cut from prolongs on the part added to the computer model for that reason. 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 of the raw materials (i.e., powder) and completed parts to verify that the incoming material meets specification requirements. Or in the case of material that is being re-used, to verify

that contamination levels have not been exceeded. In the powder bed fusion process, the powder that is not consumed in the creation of the part is re-used, but controls need to be in place because over time it will slowly become contaminated with oxides, water, partially fused surface material, and wear particles from the machine. In addition, while stridently not recommended, some companies may elect to use the same machine to process parts from multiple materials. Contamination from incomplete cleaning is a risk as a result of this practice.

3. Visual metallographic examination is 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. Reference images are usually used to compare the observed image to rejectable conditions. ASTM Standard E112 is the standard typically used to measure grain size. This test has a greater degree of subjectivity than some and as a result, needs more attention in training. (Smaller grain sizes are typically a sign of stronger material, all other things being equal)
4. Fatigue testing is sometimes conducted on parts that are critical for fatigue in service. Uniaxial specimens are very sensitive to the surface roughness of the specimen as well as machine alignment. ASTM Standard E606 is one standard frequently used. Fatigue crack growth specimens per ASTM D 647 measure the sample's resistance to the growth of a fatigue crack. These may be used in the initial qualification of a part or process, but less commonly in quality control. The specimens are quite sensitive to the humidity in the lab, testing frequency, and to machine alignment.
5. Fracture toughness testing is used to verify the materials resistance to cracks and defects. Several test specimen types are used in ASTM standard E 399. Specimens may be cut from parts, or printed by the machine. Orientation of the test coupon is important as is machine alignment. The standard contains criteria for test validity.

	YES/NO	N/A	REMARKS
Is testing being conducted in accordance with national testing standards, typically ASTM, as required by the process specification and/or manufacturing planning? (Machine alignment humidity limits should be monitored in many cases)			
Are test specimens submitted to the lab properly identified for tracking?			
Are test specimens properly stored while they await testing? (incoming materials typically)			
Are parts released prior to the results from lab testing? If so, how are they tracked if test results fail?			
Are testing standards objective and pass-fail criteria established?			
Were the samples cut in accordance with drawings specifying the locations and orientations of samples taken for testing?			
If grain size and orientation measurement is required by the specification, are they following them? (Typically ASTM) Samples will be taken from either prolongations from the actual part, test coupons printed with the parts, or destructive sampling of some parts of a print run.			
Are there objective standards for porosity, degree of consolidation, size and number of defects per unit area, available in the lab inspection?			

Are these compared with the NDI standards to monitor the capability of the NDI methods that either found the defect or failed to find it?			
Are the objective standards used in the lab under control? (Ref 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

APPENDIX 1

SAMPLING OF POSSIBLE SIGNIFICANT PROCESS PARAMETERS

Purpose:

This appendix provides a sampling of typical manufacturing processes control parameters related to additive manufacturing. Some of these parameters, when used to produce critical parts, may have upper and lower control limits established within specification limits. The part qualification and/or certification program determines which parameters require tracking of which parts and processes. Significant changes to these parameters may need requalification.
In using this appendix, we hope that the ASI will go through these parameters and note which ones are controlled and which ones are not. A parameter not checked does not imply that unsatisfactory conditions exist unless the applicable specification requires that control.

If the frozen process has an exceedance of a parameter controlled in the fixed process, an unsatisfactory condition may exist.

Scope:

This list is not all inclusive and reflects primarily the laser and electron beam powder bed fusion process. However, it does give some examples of the type of things a manufacturer involved in additive manufacturing may need to control.

The absence of one of these control procedures for any of these parameters does not imply that the process is not acceptable. It includes the following categories:

Powder, Material Parameters

- ☐ Particle size, mean, and distribution
- ☐ Reflectivity to the laser
- ☐ Chemical composition
- ☐ Cleanliness of recycled powder
- ☐ Source acceptance
- ☐ Lot acceptance testing
- ☐ Powder melt practice
- ☐ Storage condition
- ☐ Shelf life remaining
- ☐ Powder specification and classification
- ☐ Powder manufacturing process
- ☐ Powder flowability
- ☐ Condition and Handling of Powder

Machine Setup and Build Parameters

- ☐ Calibration of laser, beam output
- ☐ Recirculation filter flow rate

- [ ] Focus and alignment of beam
- [ ] Temperature of build plate
- [ ] Air or gas flow in chamber
- [ ] Oxygen sensors
- [ ] Humidity sensors
- [ ] Oxygen level at start of build
- [ ] Moisture Content
- [ ] Layer thickness
- [ ] Laser power
- [ ] Beam offset

Machine Setup and Build Parameters (cont.)

- [ ] Material that screed is made from
- [ ] Flow rates of gasses used in chamber
- [ ] Periodic machine maintenance
- [ ] Design model file
- [ ] Configuration of Build Platform
- [ ] Part location
- [ ] Part orientation
- [ ] Build envelope
- [ ] Machine manufacturer and model
- [ ] Machine serial number
- [ ] Software version
- [ ] Laser manufacturer and model
- [ ] Laser serial number
- [ ] Recoater Blade Configuration
- [ ] Recoater speed(s)
- [ ] Build platform preheat temperature
- [ ] Minimum time between layers
- [ ] Maximum time between layers
- [ ] Maximum interpass temperature
- [ ] Shielding gas composition
- [ ] Shielding gas flow rate
- [ ] Build chamber gas composition
- [ ] Supplemental gas composition
- [ ] Supplemental gas flow rate
- [ ] Type of filtration
- [ ]
- [ ]
- [ ] Beam orientation with respect to part
- [ ] Beam spot size
- [ ] Focal length
- [ ] Laser beam profile
- [ ] Pulse characteristics
- [ ] Travel speed
- [ ] Hatch pattern
- [ ] Stripe width
- [ ] Stripe overlap
- [ ] Support structure ligament thickness
- [ ] Support structure ligament spacing
- [ ] Pre exposure type (e.g., precontour)
- [ ] Skin exposure type (e.g., outerskin)
- [ ] Core exposure type (e.g., innerskin)
- [ ] Post exposure type (e.g., postcontour)
- [ ] Skin thickness (x/y)
- [ ] Skin thickness (z)
- [ ] Base radius
- [ ] Core open to platform? (Y/N)
- [ ] Skin/Core (Y/N)
- [ ] Part specific scaling
- [ ] Material dependent scaling
- [ ] Part specific undersize/oversize
- [ ]
- [ ]
- [ ]
- [ ]

General Maintenance plan

- [ ] Machine ways and bearings
- [ ] Machine interlock and safety checks
- [ ] Z-axis travel calibration/alignment
- [ ] Re-coater arm
- [ ] Gas lines
- [ ] Wiper blades
- [ ]
- [ ] Chamber temperature uniformity
- [ ] Maintenance of heaters
- [ ] Chamber vacuum pressures
- [ ] Pumps
- [ ] Door seal
- [ ]
- [ ]

Laser Maintenance Plan (as applicable)

- [ ] Power supply
- [ ] Optical to mechanical alignment
- [ ] Laser cooling equipment
- [ ] Filter replacement schedule
- [ ] Verification of pulse format
- [ ] Verification of repetition rate
- [ ] Laser Cooling water conductivity
- [ ] Laser output monitoring
- [ ] Beam focus
- [ ] Beam scan field
- [ ] Beam power and relative position
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]

Electron Beam Maintenance Plan (as applicable)

- [ ] Beam alignment
- [ ] Degaussing magnetic materials in chamber
- [ ] Filament control
- [ ] Electron Beam voltage
- [ ] Beam current
- [ ] Powder pulse sensor
- [ ] Thermocouple
- [ ] Temperature monitoring equipment
- [ ] Vacuum system and gage
- [ ] Radiation leakage checks
- [ ] Re-coater arm
- [ ] Heating chamber components
- [ ] Electron Beam gun periodic cleaning
- [ ] Chamber cleanliness
- [ ] Gas pressure
- [ ] Atmosphere
- [ ] Pre-heat of powder
- [ ]
- [ ]
- [ ]

Post Processing

- [ ] Removal of trapped powder
- [ ] Removal of integral supports, internal and external, added for manufacturing purposes
- [ ] Surface modifications (i.e. sanding, polishing, plating, powder coating, painting)

Notes

Add Comments here for items that raised questions during the evaluation, and ticklers for what items to look at in the future.