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Additive Manufacturing Mission Assurance Considerations

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Abstract

Additive manufacturing is driving an industry evolution at an accelerated rate and has been identified as a new technology with multiple mission assurance gaps in regards to qualified space hardware, including lack of released material, process and inspection specifications. As part of the 2016 Mission Assurance Improvement Workshop, a team was chartered to survey the multiple activities and capture mission assurance considerations that should be understood when faced with incorporating additively manufactured parts.

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Additive Manufacturing Mission Assurance Considerations

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Additive Manufacturing: Mission Assurance Considerations for Successful Implementation of Flight Hardware

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Problem Statement

Additive manufacturing (AM) is driving an industry evolution at an accelerated rate. There is a need to monitor industry and government mission assurance (MA) organizations that are responding to this new technology regarding materials, design, process, and inspection methods (established qualification items).

Overall effort should ensure a future path for the products to meet the quality standards and performance demands of our industry customers, including determination of what non-traditional successful AM hardware qualification programs can and should be, including primary structure.

Examples

Target audience:

- M&P communities
- MA professionals
- Scientific and academic communities
- Industry coordinated efforts

Value of topic:

- Provide overview on current AM practices for non-SME technical staff
- Develop strategy for best practices for hardware qualification process

Stakeholders

Charter

Provide a technology overview to MAIW of the technology advances, methods, materials, capabilities, and specific applications of interest to this community, including sub-area focus if necessary.

Assess and document related activities, qualification needs and considerations for accepting AM parts for flight.

Evaluate and document what qualification/certification and suitability means for AM. Review and summarize NASA Marshall draft standard as a starting point.

Products

- Produce and present technology briefing charts.

Additive Manufacturing Sub-Committee

AGENDA

- Aerospace industry standard approach to new technologies, including assessments and insertion methodology.
- What exactly is additive manufacturing (AM)?
  - *What are the technical details?*
  - *Associated technologies?*
- Details of how AM is different.
  - *NASA MSFC-STD-xxxx*: "Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware"*
  - *AM sub-committee topic explanations*
- Potential new AM technologies.

*This is a draft document and therefore has not been given a NASA designation.

Re-Assessment of Mission Assurance

- Mission assurance (MA) must be integrated into the design and build process.
- Heritage inspection processes are not always applicable to AM parts. Configurations may not be inspectable by standard processes.
- MMPDS/MIL-HDBK style material properties and process reliability are not available for AM parts.
- Part requirements and a method to validate them need to be defined during the design.
- MA needs to be actively involved in the design and fabrication of AM parts to ensure an appropriate acceptance and qualification process is followed.
- What is required for producing and delivering a part to a customer so that they will accept a part manufactured using AM?

Additive Manufactured Parts Process Overview

- Assess and identify risks of the parts and products the parts will be integrated into, e.g., consequences of failing to meet requirement(s).

- Develop qualification and acceptance programs* according to risk postures of the parts considering but not limited to:
    - Technology insertion standards
    - Parts qualification/acceptance standards
    - Material and processes standards
    - Design and analysis best practices
    - Contamination control standards
    - Product qualification/acceptance standards
    - Inspection/test requirements standards

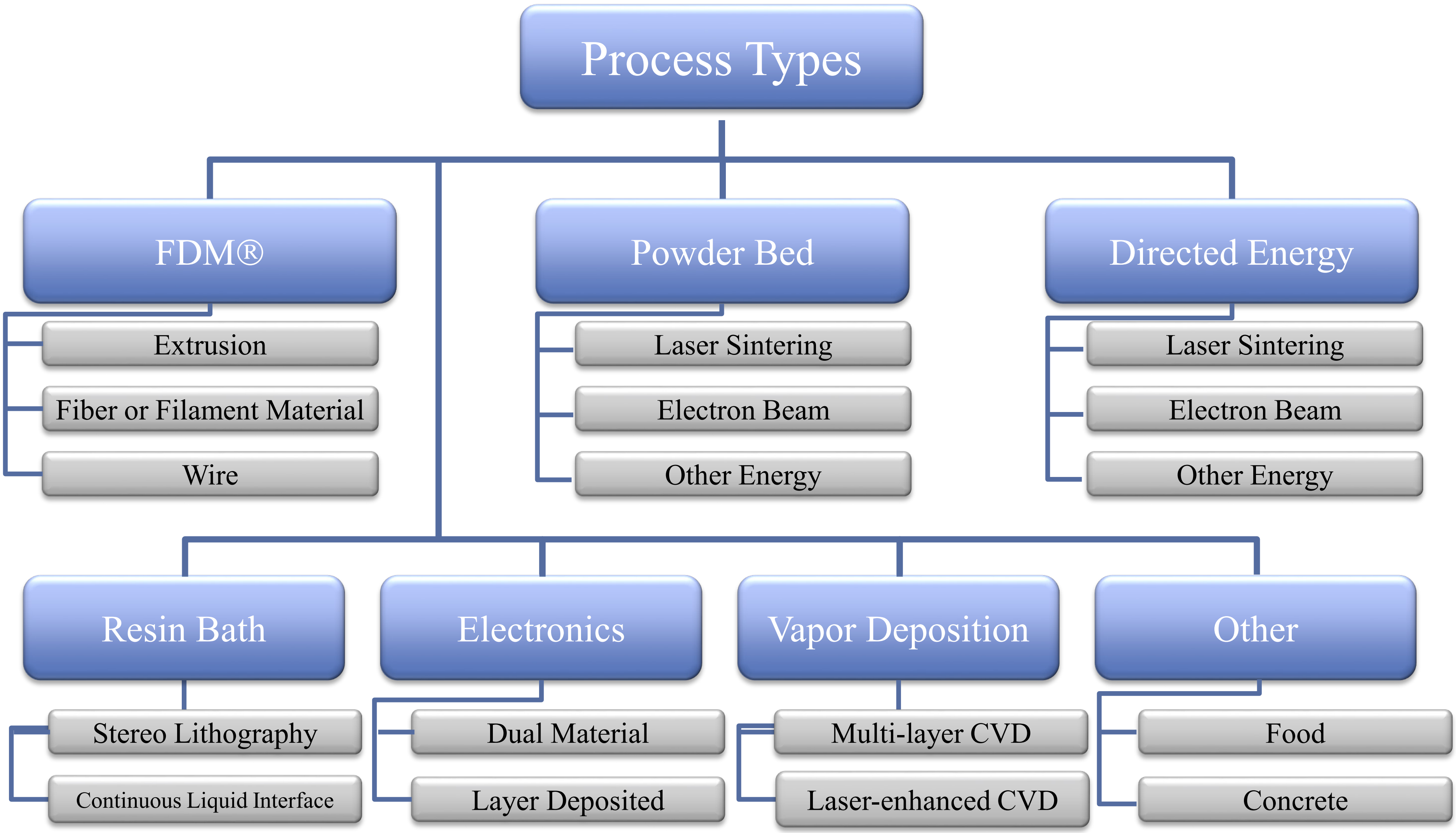
- Contractors are performing material foundries tasks.

*Note: Identical parts used on different programs must re-assess previous qualification and acceptance programs because of the different risk postures and applications.

Typical Mission Assurance Steps

- Perform tests or obtain data for applicable material properties (e.g., yield/ultimate strength, modulus of elasticity, thermal conductivity, electrical resistance, etc.).
- Perform tests on witness samples which are 3-D printed/additively manufactured along with qualification/flight parts to verify qualification/flight parts meet requirements and material properties are in-family.
- Perform tests on qualification and flight parts.
  – *Exceptions to tests are negotiated*
- Perform inspection by QA to ensure requirements are met.
  – *Only material properties that are applicable to the performance of the parts are required*
- Tests performed on 3-D printed/additively manufactured parts will be no less than the traditionally manufactured parts, e.g., machined parts.
- Other items need to be considered when developing a qualification and acceptance program, e.g., mechanical analysis assumptions—analysis of typical metallic materials assumes ductile material with elongation about 10 percent.

AM Process Types



Most Frequently Used Materials and Processes

Type	Acronym	Name	Process	Materials
FED Extrusion or filament-fed material	FDM®	Fused Deposition Modeling	Material filament fed through extruder heads	Thermoplastics (e.g., PLA, ABS, HIPS, nylon), HDPE, eutectic metals, edible materials, rubber, modeling clay, plasticine, RTV silicone, porcelain, metal clay, wax
	FFF	Fused Filament Fabrication		
	DIW	Direct Ink Writing		Ceramic materials, metal alloy, cermet, metal matrix composite, ceramic matrix composite
	RC	Robocasting		
	EBAM	Electron Beam Additive Mfg.	Wire-fed welding for material build up	Almost any metal
BED Powder bed method	SLS	Selective Laser Sintering	Powder bed layers melted with laser	Steel, titanium, nickel alloys, copper, aluminum, nylon, gold
	SHS	Selective Heat Sintering		
	SLM	Selective Laser Melting		
	DMLS	Direct Metal Laser Sintering		
	EBM	Electron Beam Melting	Powder bed with focused e-beam	
Blown Powder blown onto part melted with energy source	DE	Directed Energy	Powder entrained in an inert gas flow melted and deposited	
Scanned	SLA	Stereo-lithography	UV light on photo sensitive resin bath surface	UV sensitive resin bath

There are many other methods for concrete, food, tissue, inks, laminations, electronics, etc.

Additive Manufacturing Mission Assurance Considerations

- The following charts address the principle inquiries and significant topics regarding the additive manufacturing of metallic parts for high reliability missions. This is not meant to be a comprehensive list, but rather stimulate a conversation between mission assurance professionals and AM SMEs. Additional information has been included to provide additional background and insight into the questions related to AM.

- NASA has developed an engineering and quality standard for AM space hardware. This sub-committee will attempt to replicate NASA's established topic structure such that our efforts are complimentary, to minimize conflicting or duplicative efforts.

- NASA AM requirements which intend to provide a "measure of potential compliance" for spaceflight hardware are divided into five main categories of questions: (A) Primary Mission Assurance, (B) Equipment Controls, (C) Process Control, (D) Material Property, and (E) AM Part-Specific. Sub-categories are further delineated in the following slides.

- Most questions address one or multiple categories and are labeled as such. Other questions are more informative and do not have a category assigned.

NASA Questions by Category

A. **Primary Mission Assurance Questions:**

1. *Do all vendors in the AM process have a robust quality management system (QMS)?*
2. *Are all aspects of AM operations integrated fully into the QMS?*
3. *Is the AM vendor QMS equivalent to AS9100?*
4. *Does each vendor have a fully integrated non-conformance tracking system?*
5. *Does the AM vendor have sufficient metallurgical experience to understand, evaluate, and qualify the AM metallurgical process?*
6. *How are personnel at the AM vendor trained and evaluated for competency to operate the AM equipment?*
7. *How is the integrity of the electronic data of an AM part verified and maintained (model files, slice files, build parameter files, etc.)?*
8. *How and when is the manufacturing readiness review (MRR) process implemented for an AM part and what constitutes a successful MRR?*
9. *Does the AM build vendor have a clearly documented set of policies for conducting AM builds as a formal part of their QMS? For example, are build interruptions allowed? If so, under what circumstances?*

B. **Equipment Controls Questions:**

1. *Is there a plan that governs and tracks the maintenance, calibration, and qualification of AM equipment?*
2. *What constitutes a qualified AM machine?*
3. *What invalidates the qualified status of an AM machine?*
4. *How often are AM machines calibrated and what functionalities of the machines are included in the calibration process?*

C. **Process Control Questions:**

1. *How has the AM metallurgical process been qualified regarding the as-built quality and microstructural evolution?*
2. *What requirements exist regarding the evolution of AM microstructure through heat treatment processes?*
3. *What metrics are used to assure the AM metallurgical process is sound?*
4. *How are the quality and performance of the metallurgical process monitored over time?*
5. *How are the AM feedstock (powder or wire) controlled at time of purchase?*
6. *What feedstock controls are maintained throughout all AM operations?*
7. *How is the use of powder feedstock tracked and what policies govern the recycling of powder?*
8. *What metrics are employed to evaluate the consistency in build quality from part to part during AM production (dimensional, surface finish, coloration, detail acuity)?*
9. *What witness specimens are produced along with the AM part and what metrics are used to evaluate them?*
10. *Have all aspects of the AM part production process been documented, sequenced, and verified effective, including AM support removal, build plate removal, powder extraction, cleaning processes, and surface treatments?*

NASA Questions by Category (cont.)

D. Material Property Questions:

1. *Have material properties been developed for the AM process?*
2. *How have the material properties been verified as applicable to the AM metallurgical process intended for use?*
3. *Have all consequential influences from the AM process on material properties been accounted for in the material characterization process, such as surface finish, wall thickness, feedstock recycling, and orientation?*
4. *How has process variability been represented in the material property database?*
5. *How are process controls and process monitoring employed to ensure all AM part builds are in family with the AM materials represented in the development of material properties?*
6. *Are mechanical properties verified through destructive evaluation of the first article?*

E. AM Part-Specific Questions:

1. *Is the proposed AM part application well documented, including the consequence of failure and all associated risks?*
2. *What are the most challenging aspects of the AM build process for this part?*
3. *What are the structural demands on the AM part?*
4. *Are cyclic stresses a significant contributor to the part's load environment?*
5. *What qualification testing will the AM part be subject to?*
6. *What requirements have been defined for the first article process?*
7. *What cleanliness requirements have been established for the part and how are they verified?*
8. *Is the part proof tested and is the proof test efficacy understood relative to operational conditions?*
9. *What part inspections are performed, including non-destructive evaluations?*
10. *Are there validated NDE methods applicable to the AM part?*
11. *Is the part fracture critical or safety critical? If so, have the elements of flight rationale been articulated and substantiated?*

Additive Manufacturing Readiness Questions List

- **Primary Mission Assurance Questions:**
  1. *Do all vendors in the AM process have a robust quality management system (QMS)?*
  2. *Are all aspects of AM operations integrated fully into the QMS?*
  3. *Is the AM vendor QMS equivalent to AS9100?*
  4. *Does each vendor have a fully integrated non-conformance tracking system?*
  5. *Does the AM vendor have sufficient metallurgical experience to understand, evaluate, and qualify the AM metallurgical process?*
  6. *How are personnel at the AM vendor trained and evaluated for competency to operate the AM equipment?*
  7. *How is the integrity of the electronic data of an AM part verified and maintained (model files, slice files, build parameter files, etc.)?*
  8. *How and when is the manufacturing readiness review (MRR) process implemented for an AM part and what constitutes a successful MRR?*
  9. *Does the AM build vendor have a clearly documented set of policies for conducting AM builds as a formal part of their QMS? For example, are build interruptions allowed? If so, under what circumstances?*

Are you insourcing or outsourcing the production of the parts?

Background:	Criticality
Part fabrication requires a machine capable of aerospace-grade printing, the technical knowledge and personnel trained to run the machine, powder material handling/recycling/inspection knowledge, as well as part orientation, support structure design, and parameter prowess to properly print the part. Most companies insource and outsource plastics, and similarly metal, if they possess an in-house printer.	❑ High ✓ Med ❑ Low ❑ Best Practice

Discussion: Category: A1, A5, A9	MA Focus
Many companies in the supplier base have longer and more varied expertise in printing metal parts than OEMs. Given the production requirements for qualified parts, OEMs may see savings and improved quality by bringing printing in-house, but face a steep learning curve and rapid rate of technology evolution and standardization that the vendor base is required to maintain to remain competitive. Some OEMs are more capable of base science development which advances their technological capabilities above the vendors. Capital requirements for metal printers is a large hurdle.	✓ Contracts ❑ Inspection ❑ M&P ✓ Purchasing ✓ Requirements ✓ Source selection ✓ Statement of Work

Does the additive manufactured part act as a drop-in replacement for an existing part, or is the function/coordination entirely new?

Background:	**Criticality**
The origins and intentions of the part design, as well as the intended application, aid in determining the critical aspects required for transferring to AM manufacturing. These will affect re/qualification. Thus it is necessary to properly describe what is meant by “drop-in” replacement. Many AM designs use an identical or similar configuration, but with an altered topology necessary for AM. Minor changes in configuration may or may not impact design intent and therefore could alter intended part functionality.	✓ High ❑ Med ❑ Low ✓ Best Practice
Discussion: **Category: Informative**	**MA Focus**
• Defining “drop-in” in terms of fit, form, and function requires a pre-existing heritage part. • What are the relative and absolute design margins of the heritage and AM parts? • Is this a low- or high-risk application? Risks shall be documented such that appropriate qualification and acceptance programs are developed. • Critical design features may require additional evaluation. • Need to define part families based upon function and process. • Optimized geometry for AM is recommended to take advantage of potential improvements and also assess associated risks and mission assurance implications.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ✓ Requirements ❑ Source selection ❑ Statement of Work

What are the criteria that determine the need for qualification-by-application testing?

Background:

Application testing satisfies two needs. First, it is required as part of developing a new technology to TRL 9. Second, it is required as part of normal qualification and acceptance testing for all hardware.

To qualify AM, a stable production process must first be developed, standardized, documented, and locked. Second, material properties with a statistically sound basis must be measured for the process. Third, the material technology must be demonstrated full scale in a relevant operational environment with testing that includes static, dynamic, thermal, vacuum, acoustic, and fatigue loading. All relevant structural load events experienced through service should be identified and considered. A mode survey test verifies analytical models of dynamically complex structures. The latter will become even more important as AM is used to create lighter-weight free-form shapes that depart from traditional rectilinear geometry.

Criticality

- ✓ High
- ❑ Med
- ❑ Low
- ❑ Best Practice

Discussion: Category: A2

Qualification testing is performed on a single flight-quality item at a margin per spec. Qualification testing ensures that all structural design requirements are met and verifies both the analysis and the strength of the design. Successful qualification testing matures the item to TRL 8 and makes it ready for deployment for a mission. Successful mission deployment matures the item to TRL 9.

Acceptance testing is performed on all flight production at a margin defined by the spec as well. Acceptance testing screens for workmanship and defects and serves as a 100-percent proof test. If the margins are set correctly, the item should not incur detrimental damage that affects performance.

AM makes possible aggressively weight-optimized structures that pose a special risk for buckling. Special attention should be paid to correctly test the item under compression to verify margin against failure by buckling, which may have been a lesser concern for traditional structures. As a warning, accurate analysis and prediction of buckling behavior is non-trivial, which makes application testing all the more critical.

MA Focus

- ❑ Contracts
- ✓ Inspection
- ✓ M&P
- ❑ Purchasing
- ✓ Requirements
- ❑ Source selection
- ❑ Statement of Work

How is training managed for machine operator?

Background:	Criticality
As with any complex instrument, it is the responsibility of the end user to verify the operators have appropriate and current training for the jobs they are tasked with performing.	✓ High ❑ Med ❑ Low ❑ Best Practice
Discussion: **Category:**	**MA Focus**
Each contractor will have a specific process for ensuring appropriate training and maintaining records. Training must include machine operations but also must address all the responsibilities of the operator imposed by the QMS on the AM operations. Operators must know how to maintain quality assurance and properly handle quality escapes and mistakes. Lack of appropriate training will make quality assurance difficult to assess in AM builds. The AM build vendor needs to maintain a well-defined training program with documented metrics of trainee performance and certification levels for clear boundaries in responsibility based on the level of training.	✓ Contracts ❑ Inspection ❑ M&P ❑ Purchasing ✓ Requirements ❑ Source selection ❑ Statement of Work

What process specifications (e.g., laser sintering or electron beam melting of powder, etc.) are in place and approved?

Background:	Criticality
Additive manufacturing is highly process-dependent. The user must control dozens of parameters to ensure stable, reproducible structures. This is further complicated by the proprietary nature of many of the instruments' functions.	✓ High ❑ Med ❑ Low ❑ Best Practice
Discussion: Category:	**MA Focus**
Industry is currently developing aerospace-grade specifications for general use and, in the meantime, most companies have internal specifications for qualifying processes. The ASTM/ISO-released specification is a minimum template with additional in-house requirements as determined by each company. As a rule, each company produces process specifications to be approved by a Quality Review Board for process control of flight hardware.	❑ Contracts ❑ Inspection ✓ M&P ❑ Purchasing ✓ Requirements ❑ Source selection ❑ Statement of Work

Additive Manufacturing Readiness Questions List

Equipment Controls Questions:

1. *Is there a plan that governs and tracks the maintenance, calibration, and qualification of AM equipment?*
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Is there a machine checkout prior to build?

Background:

As part of controlling a process, the state of the AM system should be controlled to ensure that it is functioning to its expected and qualified capabilities. It is critically important to create effective minimum specific requirements for machine checkout, while operating, and after builds based upon uncertainty (of the audience/user) of continual performance.

Post-maintenance checkout may require a more detailed inspection.

Criticality

- ✓ High
- ❑ Med
- ❑ Low
- ✓ Best Practice

Discussion: Category:

- Inherent system variabilities due to hardware (energy source, beam controller, powder distributor mechanism), software (bugs, prolonged online errors, software revisions), or operator influences (maintenance or lack thereof) over time. System-to-system variabilities due to manufacturing consistency, model generational advancements, inherent process instabilities.
- Standardize checkout procedure as part of baseline manufacturing process.
- Compliance is demonstrated by a verifying performance of specific critical parameters prior to use with specific runs of part type replicates on production equipment.
- Continuous monitoring during operation can address many of the concerns of consistent performance, including a build report summary provided with each build/run.
  - Although pre-print machine checkout tends to have less influence on part quality than build monitoring, documentation of both is essential.

MA Focus

- ❑ Contracts
- ✓ Inspection
- ✓ M&P
- ❑ Purchasing
- ✓ Requirements
- ❑ Source selection
- ❑ Statement of Work

How is machine maintenance documented?

Background:

AM machines require careful maintenance. Many AM machines use fragile laser or printer technology that must be carefully monitored and that should not be used in a dirty or noisy (both electrical noise and mechanical vibration) environment. Similarly, many of the feed materials require careful handling and should be used in low-humidity conditions.

While machines are generally designed to operate unattended, it is important to include regular checks in the maintenance schedule. Different technologies require different levels of maintenance. It is also important to note that the issue of maintenance has not yet been addressed by standards, which are still under development. However, many machine vendors recommend and provide test patterns that can be used periodically to confirm that the machines are operating within acceptable limits.

Furthermore, maintenance of laser and electron guns can be very expensive, particularly for lasers and guns with limited lifetimes. The powder bed also has components (such as the wiper blade or doctor blade) that have finite lifetimes and should be checked regularly for wear.

Criticality

- ✓ High
- ❑ Med
- ❑ Low
- ✓ Best Practice

Discussion: Category:

Measuring the strength of witness coupons on an ongoing basis can verify through statistical process control that the AM process is still in control and capable and that the production machine does not need maintenance. NIST provides an AM test artifact whose geometric characteristics can be measured after maintenance and calibration occur. NIST recommends that geometric accuracy and surface roughness are useful checks. Density and Young's modulus may also be perceptive, particularly because Young's modulus is supposed to be a material invariant but often varies in AM.

The production machine needs to be on a regular calibration schedule. The heat source power (either laser or electron beam), beam steering (either galvanometer for laser or electromagnets for electron beam), mechanical components (wiper or doctor blade and platform positioning), and sieving system all require maintenance and calibration, including specimen test coupons.

It is commonly observed that the heat source is not aligned and not registered to the coordinates used on the build plate, which can introduce an off-set error.

A software update is a potential source of variation in performance. A production machine may require requalification after software updating.

MA Focus

- ❑ Contracts
- ✓ Inspection
- ✓ M&P
- ❑ Purchasing
- ✓ Requirements
- ❑ Source selection
- ❑ Statement of Work

Additive Manufacturing Readiness Questions List

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How is "lot" defined?

Background:

AM is process-sensitive. Changes in metal chemistry and thermal processing (such as build temperature, stress relief, and heat treatment) will change the material properties. In addition, AM only makes sense economically if the powder is recycled.

However, upon recycling, the powder will change size distribution and chemistry. In particular, the content of fine diameters tends to decrease, and the average particle size tends to independently increase (due to some agglomeration) during recycling. The change in powder size and distribution will affect flowability, spreading, and packing on the powder bed, as well as the beam-powder interaction. Sieving is needed to ensure uniformity of the powder bed, and the uniformity of the powder needs to be tested.

Also, the powder is liable to increase its oxygen content during recycling, which can be deleterious for Ti and can change the response to heat treating for Cu. The adsorbed water content can also change during recycling and is a potential source of hydrogen bubbles in the melt pool.

Criticality

- ✓ High
- ❑ Med
- ❑ Low
- ✓ Best Practice

Discussion: Category:

A lot is material of a specific chemical composition, heat treatment, and product form that passes through all processing operations at the same time.

Traditionally, a heat of material is material produced from a single batch melting (i.e., a single casting from a furnace) or a single furnace charge without change in processing parameters. The concept of a heat may not apply to AM because AM makes the material in-situ in each run, rather than the material being made externally in a discrete initial step. The concept of heat applies imperfectly to each production run of powder in the gas atomization step.

For AM, a lot is a single production run from one source of material (such as discrete loading of the source feed hopper or a single spool of wire) in which the material is from a single vendor production. Each AM lot sees the identical post-process heat treatment as a batch operation.

Recycling the powder should be considered a new lot until it is shown that recycling produces no statistically meaningful change in properties. As possible guidance, MIL-HDBK-5 can be adapted to account for the run-to-run variance. When the run-to-run variance is less than 25 percent of within-run variance, then two runs with recycling account for recycling's variation, and recycling is (arbitrarily) considered not to be a meaningful source of variation. When the run-to-run variance is less than 65 percent, then three runs account for the variation. When the run-to-run variance is greater than 65 percent, then five runs account for the variation.

MA Focus

- ❑ Contracts
- ✓ Inspection
- ✓ M&P
- ❑ Purchasing
- ✓ Requirements
- ❑ Source selection
- ❑ Statement of Work

What are the environmental controls over the production?

Background:

- The atmosphere and workpiece temperature are controlled.
- The processes with electron beam heating use a vacuum chamber. Arcam powder bed controls workpiece temperature by rapidly rastering a defocused electron beam at low power. Sciaky beam deposition does not control workpiece temperature.
- The processes with laser beam heating use an inert gas atmosphere (usually argon). Powder bed laser beam processes can control temperature with either IR lamps or heated base plate. The beam deposition laser beam processes do not control temperature.
- All metal welding is sensitive to oxygen, which (if present) forms an oxide surface scale that leads to poor welding of new metal on top of deposited metal. In addition, Ti is embrittled if the interstitial oxygen and nitrogen concentrations rise above 0.1 to 0.2 percent.
- The Al content in Ti-6-4 is volatile. Ti-6-4 powder can lose 0.1 percent Al upon each exposure to vacuum. Ti-6-4 can lose ~1 percent Al in the actual welding zone. The drop in Al will affect the properties and heat-treating response of the Ti-6-4.
- AM traps residual stress that can be relieved in-situ by heating the work piece.

Criticality

- ✓ High
- ❑ Med
- ❑ Low
- ✓ Best Practice

Discussion: Category:

- Atmosphere requirements include:
  - Record of the vacuum chamber’s pressure during the production run
  - Grade of the inert gas (N, Ar, or He) atmosphere and its certified gas purity and measured humidity
  - Nitrogen inert atmosphere must not be used for Ti-6-4
- Temperature requirements include:
  - Record of the workpiece temperature, if under control and if recorded with temperature sensor
- Compliance is demonstrated by:
  - Confirming that all sensors are in current calibration
  - Measuring the N and O contents in a Ti-6-4 witness sample by atomic emission spectroscopy
  - Measuring the Al content in a Ti-6-4 witness sample by wavelength dispersive spectroscopy
  - Measuring the strain-to-failure of a Ti-6-4 witness coupon
  - Confirming the part with in-situ thermal stress relief does not warp upon release from the build plate
- Remediation: mechanical properties of witness coupons can confirm that nonconformance is acceptable

MA Focus

- ❑ Contracts
- ✓ Inspection
- ✓ M&P
- ❑ Purchasing
- ✓ Requirements
- ❑ Source selection
- ❑ Statement of Work

How is the raw material controlled (supplier, lot, qualification, specification, storage, handling, etc.)?

Background:	**Criticality**
Controlling the starting feedstock material is the critical first step in having a controlled repeatable process. Unfortunately, not all critical aspects required for control are publicly understood. Different systems/settings work best with different raw material characteristics; therefore, it is not possible to write a one-size-fits-all specification. Or does the standardization issue require one universal powder specification that all system manufacturers must use? Combined lots, lot traceability, dilution of borderline or out-of-spec issues need to be defined and controlled as well.	✓ High ❑ Med ❑ Low ✓ Best Practice
Discussion: **Category:**	**MA Focus**
Addressing this issue requires powder production processes, alloy chemistry and reactivity, critical physical features/size, characterization techniques, influence of storage environment, reuse, and remixing effects. Compliance is demonstrated by means of measurement data showing chemical, physical, and performance to the specified requirements. There is additional need for further standardization. Currently, raw powder suppliers are producing the same alloys for the same systems using different specifications. Materials should be handled per spec—ASTM/ASME and/or other as appropriate.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ✓ Requirements ❑ Source selection ❑ Statement of Work

How is the process controlled (machine, settings, qualification, specification, environment, training, etc.)?

Background:	Criticality
Controlling the process is critical to attain a repeatable, long-term, cost-effective process. Not all critical aspects required for control are publicly understood. Practices vary significantly by each user. Different systems/settings work best with different raw material characteristics; therefore, it is not possible to write a one-size-fits-all standard practice.	✓ High ❑ Med ❑ Low ✓ Best Practice
Discussion: Category: C1	**MA Focus**
Standard processing technologies and critical parameters, characteristic performance, typical defects, and inspection techniques need to be documented and/or identified. Compliance is demonstrated with pre-process testing, in-situ measurements, post-process testing, and inspection It is critical to verify performance requirements are met when changes are made to settings, new machines, and standardized practices, and train personnel to those practices. AM is still very human-intensive and not plug-n-play. Process shall be controlled per spec; machine parameters on AM equipment shall be locked down; periodic validation of machine parameters shall be performed, e.g., tests on printed samples. Technologies are constantly changing; need to work to stay on top of these changes and how they affect the ability to control the processes. It is not economical to lock everything down, and difficult to control a continually evolving process. It is necessary to strike a balance through basic qualification criteria. Critical welding operations or composites fabrication approaches are analogous to AM.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ✓ Requirements ❑ Source selection ❑ Statement of Work

How are the build plate and supports removed?

Background:	Criticality
Build plates and supports are an integral aspect of AM. It is critical to plan for the removal of the ancillary support structures necessary to successfully complete a build.	❑ High ✓ Med ❑ Low ✓ Best Practice

Discussion: Category:	MA Focus
Typically wire EDM is used to reduce imparting heat and stress. Other machining methods can be used for post-heat-treat methods where thermal stress relief has occurred. It should be noted that larger bulk parts or non-symmetric parts tend to have large thermal stresses that may crack or warp the part if not annealed. Some parts may be removed without annealing if it is known thermal stresses are not sufficient to warp part after removal. Support structures typically require standard machining processes for removal. Visual inspection to ensure support removal is suggested.	❑ Contracts ❑ Inspection ✓ M&P ❑ Purchasing ❑ Requirements ❑ Source selection ❑ Statement of Work

Additive Manufacturing Readiness Questions List

Material Property Questions:

1. *Have material properties been developed for the AM process?*
2. *How have the material properties been verified as applicable to the AM metallurgical process intended for use?*
3. *Have all consequential influences from the AM process on material properties been accounted for in the material characterization process, such as surface finish, wall thickness, feedstock recycling, and orientation?*
4. *How has process variability been represented in the material property database?*
5. *How are process controls and process monitoring employed to ensure all AM part builds are in family with the AM materials represented in the development of material properties?*
6. *Are mechanical properties verified through destructive evaluation of the first article?*

Are the material (metals) and process used elsewhere in the aerospace industry?

Background:

1. There is a wide range of metal AM processes. Each process has specific attributes (size, build rate, geometric complexity, cost, and ideal alloys) that lend themselves to certain components.
2. Because of its high cost and widespread usage, Ti-6Al-4V has been the primary alloy of focus. Next has been Ni-base, also due to cost interest, but also because of the complexity of many Ni-base components. Interest has begun on Al alloys, not because of cost considerations (machined from solid is quite competitive), but because of complexity and lead time for that complexity.

Criticality

- ✓ High
- ❑ Med
- ❑ Low
- ✓ Best Practice

Discussion: Category: A5 D

1. The wide range of commercially available processes and machines pretty much covers the full range of components that are needed. What is needed is confidence in the ability of the systems to produce sound, consistent, nondestructively tested components, with acceptable surface finishes. After this is achieved, it will be necessary to lower the operating cost and throughput of the machines to provide affordable components.
2. Because of the challenges in developing and qualifying new material systems, the emphasis so far has been on existing alloys that are either castable or weldable. As confidence in AM grows, new alloy systems will be investigated that take advantage of the generally rapid solidification present in AM, and also that can prevent columnar growth. Interest in functionally graded materials will start simple (IN625 to IN718), and will only move to more complex systems when means overcome CTE mismatch and detrimental intermetallic formation are developed.
3. It is also critical to understand an AM version of a material does not possess the same mechanical properties as a wrought or cast material. There will be some differences.

MA Focus

- ❑ Contracts
- ✓ Inspection
- ✓ M&P
- ❑ Purchasing
- ✓ Requirements
- ❑ Source selection
- ❑ Statement of Work

What are the part design material allowables based on?

Background:	Criticality
The design allowable values establish the baseline performance expectations for the part design. It is critical to understand the design applications in order to properly establish the material allowable test regime. In the AM process, there are a wide variety of variables to account for (raw material lot sampling, reuse, orientation, temperature, sizing effects, post-build processes). And it is costly to adjust process. It is critical to understand the impact of different parameters as well as variability between similar systems.	✓ High ❑ Med ❑ Low ✓ Best Practice
Discussion: **Category:**	**MA Focus**
Data has to be established to determine the effect of orientation, size/scale, surfaces and finishing processes, virgin versus reused powders. As well as developing the test procedures to demonstrate compliance—i.e., mechanical test coupons taken from multiple locations within the build area and over multiple builds—other discussions might include monitoring for significant statistical population distribution as well as demonstrating that all orientation/scale dependencies are accounted for in the test regime. A-, B-, and S-basis per design requirements if data exist, and witness samples (quantity TBD) shall be analyzed and used to confirm build parts meet requirements. Note: design allowables for additive parts shall be provided for all directions (to address anisotropic material properties). Material properties for simultaneous multi-axial loading shall be addressed as TBD. Geometry typical traveler specimens need to be defined as well.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ✓ Requirements ❑ Source selection ❑ Statement of Work

What is the design margin value for the AM part?

Background:	Criticality
Design margin provides a quasi-numerical buffer between what is required for performing the role and what the part can actually achieve; that is, if you believe the analysis and the numbers used to generate the final margin value. Audience is left with less confidence in the material allowables test regime used to generate the strength allowables or the simulation used to generate the stress on the part. Lower-design margin values are meaningless without testing to verify part strength and having a thorough understanding of how the value of the design margin was generated in the first place; i.e., it's a soft, short answer. Difficult to state a minimum required design margin value across the board. Many layers to the final margin value that cannot be understood or can always be effectively communicated to the audience. Knock-down factors are also an option such that they may be relieved once future process improvement/stabilization occurs.	✓ High ❑ Med ❑ Low ✓ Best Practice

Discussion: Category: D1	MA Focus
Given established requirements, analysis techniques and assumptions, dynamic environment simulated, secondary and tertiary part interactions, strength allowables, and material test regime, and understanding of the actual operation environment and conditions. No textbook black-and-white go/no go value. The design margins are evaluated by physical testing during qualification of the part to measure the performance and compare to the analysis work. Proof of performance can only be verified by testing and use. The design margin is an intermediary value until reality takes over. Note: update de-rated material properties as technology evolves and matures. Using this approach, there is no need to change current design factors. It is important to note the design margin value is too complicated to accurately communicate the nuances. Therefore, the final value that is presented is always going to be questioned and simple communication will be lost. Comparable approach for traditional fabrication techniques. See new metal alloys development and use.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ✓ Requirements ❑ Source selection ❑ Statement of Work

How do you validate AM part performance based on build orientation (assuming dependence of properties on orientation)?

Background:	Criticality
Values must be established for the baseline performance expectations for the part design. It is critical to understand the design applications in order to properly establish the material allowable test regime. If this is not done, the audience is left with less confidence in the material allowables test regime and how to adequately ascertain the given orientation, and requires additional testing to ensure that all possible orientations and locations are statistically characterized.	✓ High ❑ Med ❑ Low ✓ Best Practice

Discussion: Category:	MA Focus
It is important to understand the effects of orientation and location within a build chamber and their effect on the thermal and physical interactions between the consolidated and unconsolidated regions during fabrication. The orientation effects must be evaluated using a baseline coupon test set to establish the limiting orientations and locations. Build coupon testing in those orientations to verify minimum expected performance through destructive testing. If data does not exist, develop a risk mitigation program and obtain a waiver against material allowables. Note: passing qualification/proto-flight level tests does not provide sufficient proof that design allowables are met. Drawings and/or models shall denote build orientations, and as-built parts shall be verified per drawing/model requirements.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ✓ Requirements ❑ Source selection ❑ Statement of Work

Additive Manufacturing Readiness Questions List

AM Part-Specific Questions:

1. *Is the proposed AM part application well documented, including the consequence of failure and all associated risks?*
2. *What are the most challenging aspects of the AM build process for this part?*
3. *What are the structural demands on the AM part?*
4. *Are cyclic stresses a significant contributor to the part's load environment?*
5. *What qualification testing will the AM part be subject to?*
6. *What requirements have been defined for the first article process?*
7. *What cleanliness requirements have been established for the part and how are they verified?*
8. *Is the part proof tested and is the proof test efficacy understood relative to operational conditions?*
9. *What part inspections are performed, including non-destructive evaluations?*
10. *Are there validated NDE methods applicable to the AM part?*
11. *Is the part fracture critical or safety critical? If so, have the elements of flight rationale been articulated and substantiated?*

How is each AM build verified?

Background:

- Depending on the specific AM technology (powder bed, wire-fed, or blown powder), non-destructive inspection of the hardware may be achieved through a number of ways. These can include traditional NDI methodology, CT, or X-ray.
- A statistically significant number of destructive articles are typically fabricated with hardware to ensure mechanical property integrity.
- Build logs on the machine are analyzed for abnormalities of key processing parameters during hardware construction.
- Raw material certification documentation is checked to ensure chemistries are met along with particle size distributions or wire attributes.

Criticality

- ✓ High
- ❑ Med
- ❑ Low
- ✓ Best Practice

Discussion: Category: E5, D6

- AMS4999A and AMS4998 provide details on Ti 6Al-4V minimum tensile properties, coefficient of variation of mechanical properties, radiographic inspection, material quality, etc.
- How should key processing parameters be defined or agreed-upon to ensure process consistency? Note that not every aerospace manufacturing company may agree on key processing parameters. It would depend on the requirements of the application being defined for AM. How would this affect common specification development?
- When machine manufacturers upgrade AM machines, build verification may change. Specifications around AM builds should be dynamic enough to adjust to new technology enhancements that are forthcoming on AM machine platforms.

MA Focus

- ❑ Contracts
- ✓ Inspection
- ✓ M&P
- ❑ Purchasing
- ✓ Requirements
- ❑ Source selection
- ❑ Statement of Work

Are these parts already on a program?

Background:	Criticality
It is important to identify parts as AM-fabricated to ensure that they can meet the design intent.	❑ High ✓ Med ❑ Low ❑ Best Practice
Discussion: **Category:**	**MA Focus**
A risk assessment shall be performed and recommendations shall be presented to a board (e.g., Senior Management Review Team [SMRT]) to determine if the part can be accepted for flight. Direct replacement applications are few and parts generally need to be altered for AM processing.	❑ Contracts ❑ Inspection ❑ M&P ❑ Purchasing ✓ Requirements ❑ Source selection ❑ Statement of Work

How is fatigue/dynamic loading mitigated?

Background:	Criticality
Fatigue/dynamic performance is a critical factor in understanding the performance of additively manufactured parts.	❑ High ✓ Med ❑ Low ❑ Best Practice
Discussion: **Category:**	**MA Focus**
Fatigue analysis shall be based on material test data. If no fatigue test data is available, employ a de-rate factor against yield (e.g., X%) as a criteria to determine if a part is fatigue critical. If the equivalent static analysis demonstrates zero or greater margin against the de-rated allowables, the part is deemed not fatigue critical.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ❑ Requirements ❑ Source selection ❑ Statement of Work

How are the parts cleaned?

Background:	Criticality
Metal printed parts are inherently “dusty” with residual powder from the AM process. Additionally, metal powder has a tendency to tenaciously reside in cavities and rough surface features. Completely removing powder that is dense and other printing byproducts can be difficult. Desired cleanliness varies for part application (brackets versus biocompatible implants or high-speed turbines). The intention of this question is to ensure that contamination and surface-finish requirements are met.	❑ High ✓ Med ❑ Low ✓ Best Practice
Discussion: Category: E7	**MA Focus**
Different cleaning methods are employed depending on end use of the AM part. Simple dusting, water, or solvent wash, up to ultrasonic cleaning or super cleaning may be called out in process or drawing requirements. Passage flushing operations (air or fluid) also may be employed as are many standard cleaning methods. Wiping or rinsing the part and examining the wipe media or rinse fluid for residual particulate, or even X-ray/CT scans for clogged internal passages/cavities, may also be employed. Current cleaning processes shall be employed to clean parts. Develop and validate cleaning processes for rough surfaces of additive parts as required—visibly clean is a subjective assessment.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ✓ Requirements ❑ Source selection ❑ Statement of Work

What type of defects are there and how are they controlled?

Background:	Criticality
There is a wide variety of defects that require definition for AM that are, and are not, similar to existing manufacturing defects. Their ability to be discovered through current inspection techniques as well as their acceptability by size, density, or effect on material properties are not characterized. Additionally, there are new or extrinsic defects (residual stress) that can occur with little similarity to existing manufacturing methods, that need to be categorized and assessed as to whether they even affect material properties.	✓ High ❑ Med ❑ Low ✓ Best Practice
Discussion: Category:	**MA Focus**
Defect discovery and characterization for AM manufactured parts will require an industry assessment of inspection capability with current technologies. Surface-finish effects on CMM and light-based measurement accuracy is not well-characterized nor are hermitic surfaces or crack determination methods (dye penetrant). Internal density, inclusions, grain anomalies, material adulterations from alien powders, recycle limits of in-use powder, etc. will all require parameter definition and implications for acceptability/control. Current MRB processes shall be used. Develop QA processes for AM parts as required.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ✓ Requirements ❑ Source selection ❑ Statement of Work

How do you inspect and accept/reject parts?

Background:	Criticality
Non-destructive part inspection versus acceptance testing is the industry standard for quality assurance of production parts. As AM fabrication produces a rough surface finish while allowing for, and implicitly increasing, contours, cavities, and internal feature complexity, traditional CMM, handheld tool, and visual inspection techniques are insufficient to inspect configuration and internal part integrity. As such, acceptance criteria and techniques are borderline insufficient or prohibitively expensive for some AM parts.	✓ High ❑ Med ❑ Low ✓ Best Practice
Discussion: Category:	**MA Focus**
Inspection capabilities and accepted industry standards for appropriate capabilities need to be developed and defined for degrees of criticality. CT, X-ray, white/blue/structured light grades as well as traditional methods need to be assessed for their applicability to AM parts with regard to surface roughness and internal inspection. FAI of sectioned parts will only be reliable when process repeatability for surface control (finish, tolerance, cracks, etc.) is defined and understood. Current QA processes shall be used. Develop QA processes for additive parts as required.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ✓ Requirements ❑ Source selection ❑ Statement of Work

What dynamic conditions are there and have the parts been tested for them?

Background:	Criticality
Dynamic conditions can be a far greater test for materials than static applications. The fabrication nature of the AM process affects grain structures, inclusions, anisotropic properties, etc., with known complexities and impacts on part integrity, fatigue, and other dynamic condition performance factors. Given the complex nature of dynamic applications, what history of use can be drawn from for similar applications?	✓ High ❑ Med ❑ Low ✓ Best Practice
Discussion: Category: E3 E4	**MA Focus**
Small turbines, engine components, and surgical implants have been printed with varying degrees of success. A scaled jet engine has been made and tested along with long-term wear/friction data from knee implants. Test results for these applications are highly proprietary as performance data of specifically designed configurations are necessary for a competitive edge. Thus this question will have limited value beyond the press release data sources.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ✓ Requirements ❑ Source selection ❑ Statement of Work

What is the yield rate of the machines that are being used?

Background:	Criticality
First-part 100-percent success rate is low for most families printing. Most first prints require additional improvements for a successful print. Yields after the first few builds tend to have high success rates (above 90 percent) once part and build design standard processing is established.	❑ High ❑ Med ✓ Low ❑ Best Practice
Discussion: Category:	**MA Focus**
The formal “successful” yield rate needs to be defined for what is acceptable per inspection techniques (defect definition, porosity, etc.). Parts tend to be designed with comfortable margins reflecting the uncertainty of current fabrication assurance and lack of fully developed properties and in-service history. As such, yield rates for conservative applications and larger production counts with sufficient testing are considerably higher than single-point solutions with critical performance needs. Many parts are deemed useable “as-is” knowing the risk of the new process in research applications.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ❑ Requirements ❑ Source selection ❑ Statement of Work

What post-finishing processes are required?

Background:

- After production, the part may suffer from defects or undesirable features:
  - High residual stresses may be caused by the high thermal gradients from the rapid solidification of the molten weld pool
  - Poor surface finish, which decreases high cycle fatigue life
  - Undesired excess skin of incompletely sintered powder caused by heat transfer across part’s perimeter
  - As-produced density of 95 percent
  - As-welded microstructure that is typically layered in the build direction
  - Attached scaffolding to support an overhang, steep build angle, or the top of a hole
  - Remnant or trapped unconsolidated loose powder
  - Microstructure that does not provide correct mechanical properties

Criticality

- ✓ High
- ❑ Med
- ❑ Low
- ✓ Best Practice

Discussion: Category:

- Residual stresses are caused by a section of the part permanently deforming plastically, which is balanced by equal and opposite elastic stresses elsewhere. The part distorts and warps when it is removed from the constraint of its build plate.
- The incompletely sintered skin can serve as FOD liberated during service or as a starter crack for fatigue and fracture. (See NISTIR8036 and *Met and Mat Trans A*, vol. 44A, pp. 1010-1022)
- The as-produced surface finish is variously given as 12 to 20 microns (500 to 800 μinches) Ra and 8 to 15 microns (300 to 600 μinches) Ra. The surface finish is worse for electron beam heating (600 μinches Ra) than for laser beam heating (300 μinches Ra). The surface finish is also typically three times worse on the sides of the build than on the top. The rough surface finish is responsible for worse fatigue and fracture properties.
- The microstructure often corresponds to a rapidly cooled non-equilibrium state for laser beam heating and an annealed slowly cooled state for electron beam heating.
- Porosity can be caused by incomplete fusion or by entrapped argon. The porosity is usually worse in the build (Z-direction), which is partly responsible for the worse properties in this direction.
- Removing the scaffolding can leave residual witness marks requiring further smoothing.
- After part removal, the build plate has to be resurfaced flat and smooth. The machine manufacturer can specify different surface finishes for different metal build plates.

MA Focus

- ❑ Contracts
- ✓ Inspection
- ✓ M&P
- ❑ Purchasing
- ✓ Requirements
- ❑ Source selection
- ❑ Statement of Work

How are post finishing processes are accomplished?

Background:

- The different post-finishing processes are:
  - Reducing residual stresses
  - Improving surface finish of produced part
  - Densifying the part to reduce porosity
  - Heat-treating to remove as-welded microstructure or to give desired microstructure
  - Removing scaffolding
  - Removing remnant or trapped unconsolidated loose powder
  - Refinishing the build plate

Criticality

- ✓ High
- ❑ Med
- ❑ Low
- ✓ Best Practice

Discussion:

Category:

- Between deposition steps, Arcam machine can raster a low-energy defocused electron beam, which can heat the workpiece uniformly during production, eliminating residual stress. Production machine with laser beam heating requires furnace annealing before removing the workpiece from the build plate.
- The surface can be finished by shot peening, grit blasting, abrasive flow smoothing, or machining (milling, lathe, grinding, or polishing). Shot peening can also leave a beneficial compressive stress on the surface that improves the fatigue performance.
- For densification, hot isostatic pressing (HIP) is performed at an argon pressure of 15,000 psi (106 MPa) and a temperature of about 3/4 of the homologous melting point on an absolute scale for two to four hours. The density can be improved from ~95 percent to >99 percent. HIP improves the ductility, ultimate tensile strength, and fatigue properties, but can lower the yield strength because the as-produced fine grain size coarsens. HIP can also anneal the residual stresses and recrystallize the as-welded microstructure. HIP can also repair crack-like planar defects caused by lack of fusion.
- Heat-treating recrystallizes the as-welded layered microstructure and replaces it with a more equiaxed microstructure. Heat-treating can also produce the desired strength and ductility. In some cases, the as-produced microstructure can meet most or all mechanical properties.
- Scaffolding is removed by wire EDM, band saw, or manually cutting. The scaffolding can be attached to the workpiece with spaced teeth that break away easily.
- The powder can be removed automatically with a vacuum-assisted vibratory screen or manually with a brush and compressed air. The poorly sintered skin is removed by shot peening. Powder trapped internally can be removed with a chemical etchant. Trapped powder is worse for electron beam heating.
- The build plate is ground or milled smooth and flat.

MA Focus

- ❑ Contracts
- ✓ Inspection
- ✓ M&P
- ❑ Purchasing
- ✓ Requirements
- ❑ Source selection
- ❑ Statement of Work

When should part qualification by analysis be acceptable?

Background:

- NASA-STD-5001B, *Structural Design and Test Factors of Safety for Spaceflight Hardware*, has excellent guidance on verifying structural integrity by analysis alone without strength testing, and much of this information is drawn from it.
- AM and casting are both solidification processes, and both are also process-sensitive. AMS2175, *Castings, Classification and Inspection of* can, therefore, provide guidance relevant to additive manufacturing.
- An acceptable engineering rationale and project-specific criteria for the “no-test qualification by analysis” option shall be provided for review and approval by the SPO.
- The “qualification by analysis” approach has a larger factor of safety than tested hardware.
- However, the larger safety factor doesn’t by itself justify the “qualification by analysis” approach.

Criticality

- ✓ High
- ❑ Med
- ❑ Low
- ✓ Best Practice

Discussion: Category:

- The following criteria justify “qualification by analysis”:
  - The structure is simple with easily determined loads and stresses. The design has been thoroughly analyzed for all critical loadings with high confidence in the load magnitudes.
  - The structure in question resembles or shares the design, build quality, process control, material allowables, and loads of a previously evaluated structure. This previously evaluated structure will have been verified by testing with good correlation to analysis.
  - During development, tests have been completed on critical structural components that are difficult or uncertain to analyze. Test results correlate well and validate the analysis.
- NASA Goddard’s GSFC-STD-7000, *General Environmental Verification Standard*, provides the factors of safety for “qualification by analysis”: 2.0 on yield strength and 2.6 on ultimate strength.
- For no qualification test, AIAA S-110-2005 provides a design factor of safety on limit loads: 1.6 against yield and 2.0 against ultimate failure.
- However, AIAA S-110-2005 recommends that “qualification by analysis” typically applies to one-of-a-kind or modification to existing structure and does not typically apply to a fleet.
- AMS2175 does not require radiographic inspection of a casting with margin of safety greater than 2.0. Radiography can be considered similar in spirit to physical testing. AMS2175 does not distinguish, however, between yield and ultimate strengths, which is less conservative than GSFC-STD-7000 but at least as conservative as AIAA S-110-2005.

MA Focus

- ❑ Contracts
- ✓ Inspection
- ✓ M&P
- ❑ Purchasing
- ✓ Requirements
- ❑ Source selection
- ❑ Statement of Work

How are residual stresses controlled and reduced?

Background:	Criticality
The residual stress in an AM-fabricated structure can be very complex depending on a number of process variables. It is important to understand the residual stress state of AM structures to avoid distortion and/or premature failure.	✓ High ❑ Med ❑ Low ❑ Best Practice
Discussion: Category:	**MA Focus**
Stress-relieved requirements shall be determined by an appropriate review board. Note: additive manufactured parts might require the development of new stress-relieved processes. This may include post-build thermal treatment as well as attention to hatch patterns, build plate temperatures, laser residence periods, and wattage.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ❑ Requirements ❑ Source selection ❑ Statement of Work

How is loose powder removed and verified?

Background:	Criticality
Powder removal in AM parts is an important aspect in AM fabrication. The build plan should discuss the cleanliness requirements of the structure and the verification process.	✓ High ❑ Med ❑ Low ❑ Best Practice
Discussion: Category: E7	**MA Focus**
Current cleaning processes shall be employed to clean parts. Develop and validate cleaning processes for rough surfaces of AM parts as required—visibly clean is a subjective assessment. The intention of this question is to ensure that contamination and surface-finish requirements are met.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ❑ Requirements ❑ Source selection ❑ Statement of Work

Is the surface treated or finished after production?

Background:	Criticality
The surface finish of AM-produced structures can have a significant impact on the parts performance (fatigue assessment, cleaning, other properties). It is important that surface finish be accounted for in the desired application.	✓ High ❑ Med ❑ Low ❑ Best Practice
Discussion: Category:	**MA Focus**
(Surface) finishing processes for current parts might not be applicable, necessary, or possibly employed for additively manufactured parts. The design of AM parts shall take into account voids and rough surfaces of the final product. Grit blast, peening, cladding, anodizing, etc. may be desired for final part surfaces if required.	❑ Contracts ❑ Inspection ✓ M&P ❑ Purchasing ✓ Requirements ❑ Source selection ❑ Statement of Work

Support Structures in Additive Manufacturing

Background:

Fabricating complex geometries with the AM build process can require sacrificial support structures to aid in dimensional stability and feature location of the final part.

Benefits:

- Ease of removal from platen
- Anchor overhangs and floating sections during the build
- Strengthen tall-thin structures
- Prevent thermal distortion

Costs:

- Additional build time and material usage
- Additional post-build labor (remove support/polish surface)
- Potential limitations in available build geometries
- Temp. structure should facilitate removal of powder prior to post processing

Criticality

- ❑ High
- ✓ Med
- ❑ Low
- ✓ Best Practice

Discussion: Category:

Build angles <~ 45˚, overhangs > ~ 3 mm require support structures.

Build software provides initial support layout.

Design rules in place in commercial software

Structure requirements can be modified by optimizing the build orientation

See (potential impact of build orientation on part performance)

Use dimensional inspection to ensure correct build and no distortion.

First article/engineering model will verify.

Heat-treat prior to removal of support structure.

MA Focus

- ❑ Contracts
- ✓ Inspection
- ✓ M&P
- ❑ Purchasing
- ✓ Requirements
- ❑ Source selection
- ❑ Statement of Work
- ❑ Scheduling

How is machine cleanliness verified following powder change out?

Background:	Criticality
Powder contamination resulting from previous builds can significantly impact the build quality of an AM part.	✓ High ❑ Med ❑ Low ❑ Best Practice
Discussion: Category:	**MA Focus**
It is critical to develop a process for changing out powders in the AM system while minimizing the potential for contamination. Machine internal cavities and hoses provide a risk for trapped powder removal. Care must be taken for this material removal. Support equipment such as powder reservoirs and handling equipment should receive similar and appropriate attention.	❑ Contracts ✓ Inspection ✓ M&P ❑ Purchasing ❑ Requirements ❑ Source selection ❑ Statement of Work

What safety issues are involved in AM?

Background:	Criticality
Metal powders can be dangerous and may be inhaled. Specifically aluminum and titanium are explosive. Lasers are high-energy devices. Argon is an inhalant gas. Static discharge and flammability are also hazards associated with AM. AM machines combine all of these.	✓ High ❑ Med ❑ Low ❑ Best Practice
Discussion: **Category:**	**MA Focus**
Handling, operation, and health concerns have multiple concerns that need in-depth discussion far beyond this project. It is paramount to educate all personnel working on metal printing machines.	❑ Contracts ❑ Inspection ❑ M&P ❑ Purchasing ❑ Requirements ❑ Source selection ❑ Statement of Work ❑ SAFETY

BACKUP

Acronyms

AIAA	American Institute of Aeronautics and Astronautics
AM	Additive Manufacturing
AMS	Aerospace Materials Specifications
AMUG	Additive Manufacturing Users Group
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CMM	Coordinate measuring machine
CT	Computed tomography
CTE	Coefficient of thermal expansion
DED	Directed energy deposition
DMLS	Direct metal laser sintering
EDM	Electrical discharge machining
EWI	Edison Welding Institute
FAI	First article inspection
HIP	Hot isostatic pressing
ISO	International Standards Organization
JHU/APL	Johns Hopkins University/Applied Physics Laboratory
M&P	Manufacturing and processing

Acronyms (cont.)

MA	Mission Assurance
MIT/LL	Massachusetts Institute of Technology/Lincoln Laboratories
MRR	Manufacturing readiness review
NASA	National Aeronautics and Space Administration
NDE	Nondestructive evaluation
NDI	Nondestructive inspection
NIST	National Institute of Standards and Technology
OEM	Original equipment manufacturer
QA	Quality assurance
QMS	Quality management system
SAE	Society of Automotive Engineers
SME	Subject matter expert
SMRT	Senior management review team
SSL	Space Systems Loral
SWE	Society of Woman Engineers
TRL	Technology readiness level

See Slide 7 for industry-accepted process acronyms for AM technologies

Original Questions

- Does the AM part act as a drop-in replacement for an existing part, or is this a totally new function/coordination?
- How is the raw material controlled (supplier, lot, qualification, specification, storage, handling)?
- How is process controlled (machine, settings, qualification, specification, environment, training)?
- What are the part design material allowables based on?
- What is the design margin value?
- How is each build verified?
- What is the qualification plan for the part (mechanical, analysis)?
- What other parts have been made to perform a similar function?
- Are these parts already on a program?
- How is fatigue/dynamic loading mitigated?
- How is the performance of small length scales verified/known?
- Are the material and process used elsewhere in the aerospace industry?
- Are the parts within a part family that is currently flying and/or qualified?
- How are the parts cleaned?
- What type of defects are there and how are they controlled?
- How do you inspect and accept/reject parts?
- What dynamic conditions are there and have the parts been tested for them?
- What is the yield rate of the machines that are being used?
- Are you insourcing or outsourcing the production of the parts?
- How much experience does the company and operators have using AM technology?
- What are the environmental controls over the production?
- What post-finishing processes are required?
- How are the post-finishing processes accomplished?
- When should part qualification-by-analysis be acceptable?
- What are the criteria (stress, feature size, operating environment, part family) for determining the need for qualification-by-application testing?
- In specific for post-finishing, is the part heat-treated or hot-isostatically pressed?
- How are residual stresses controlled and reduced? Are the residual stresses measured?
- How are the build plate and supports removed?
- How is loose powder removed? What is the risk for FOD?
- How is the removal of powder and supports verified?
- Is the surface treated or finished after production?
- What is the orientation dependence of properties?
- Is the microstructure (grain size, grain shape, and phases) verified through metallography?
- Is the porosity measured?
- How is the produced part verified to match the design?
- Are witness samples made during each production run?
- Are controls required for handling, storage, and environment?
- How do you validate build orientation (assuming dependence of properties on orientation)?
- Is there a machine checkout prior to build?
- What happens if power is interrupted during build?
- How is part spacing determined/controlled during build?
- How are machines qualified?
- How is surface roughness controlled?
- How is a “lot” defined?
- How is machine maintenance documented?

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