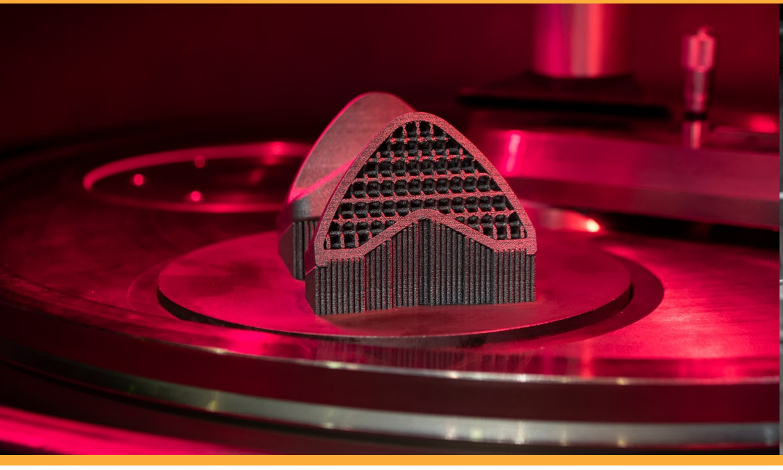

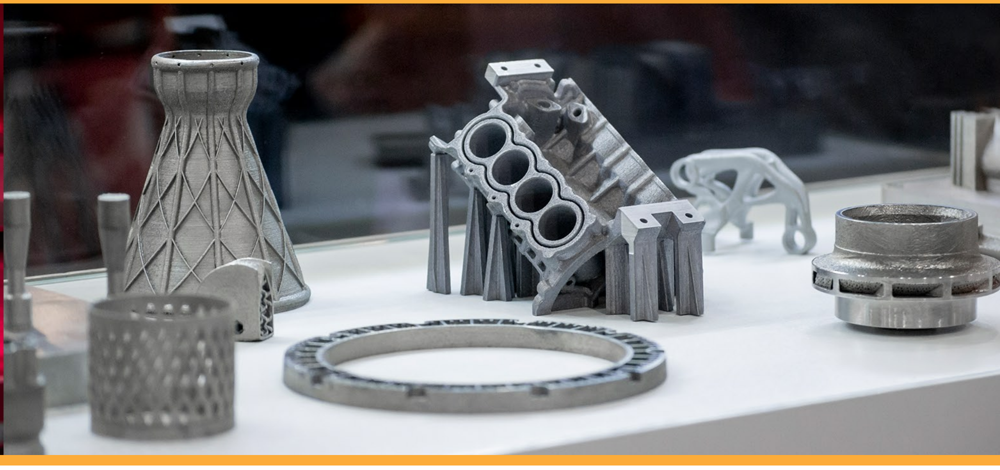

# Recommended Guidance for Certification of AM Component

AIA Additive Manufacturing Working Group

February 2020

# INTRODUCTION

## 1 Key Words

Airframe, Airplanes, Commercial, Transport, Engines, Powerplant, Rotorcraft, Additive Manufacturing, Qualification, Certification, 3D Printing

## 2 Disclaimer

The views expressed herein are endorsed by the members of the Aerospace Industries Association (AIA) Additive Manufacturing (AM) Working Group[1] and do not necessarily reflect the views of the organizations that they represent. The FAA has participated on this AIA committee; however, conclusions stated within this report do not necessarily represent the views of the FAA.

## 3 Executive Summary

Additive manufacturing is quickly growing in aerospace for production use because of weight savings, design freedom, flow time reduction, and cost savings. Today's state-of-the-art equipment is increasingly utilized for fabricating components in prototyping while production clearance still presents a significant challenge in assuring part-to-part repeatability. The AIA Working Group for Additive Manufacturing was asked by the Federal Aviation Administration (FAA) to collaborate on a report addressing the unique aspects of certifying AM components for aerospace applications. This paper also provides guidance for compliance to 14 CFR 2x.603, 2x.605, 2x.613, 23.2260, 33.15, and 35.17 for metal powder bed fusion (PBF) and directed energy deposition (DED) additive processes. Additional guidance may be required for higher criticality parts subject to FAA rules 14 CFR 23.2240, 14 CFR 2X.571, 14 CFR 33.14, 14 CFR 33.70, and 14 CFR 35.37. This report delves into considerations and current industry best practices in the areas of material/process development, part/system qualification, and development of material allowables and design values. The authors are aerospace industry design approval holders and users of the equipment, and hence provide an experienced and qualified perspective on these issues. In summary, the key milestones can be achieved using established and proven methodologies as the basis, coupled with added focus on issues unique to AM. This report is a collection of recommended best practices and may be given further consideration as a basis of, in part or in whole, a means of compliance to applicable regulations.

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[1] The Working Group was formed in 2015 by the Aerospace Industries Association with the objective to support development of effective and consistent guidance for design, manufacture, and certification of parts produced via additive manufacturing processes.

## 4 Contents

# 5 Background

Additive manufacturing has great potential in the aerospace industry as a disruptive technology for component fabrication. Increasing use in production due to opportunities for weight reduction, design flexibility, "fail fast/learn fast" prototypes, reduced development time, rapid resolution of supply chain challenges, and cost savings make this technology attractive for aerospace production. However, while current powder bed fusion and directed energy deposition machines are highly capable for prototyping, there is a need to establish material and process controls if part certification is to be considered. Whether by public domain standards or proprietary standards, these controls are reliant on end-user protocols that assure part-to-part repeatability, in terms of material properties and part function. While currently used aerospace product development methodologies still apply (e.g., risk assessments, qualification test planning, etc.), AM-specific process controls need to be developed.

## 5.1 Scope

This report outlines key activities that Design Approval Holders (DAH) should undertake when seeking FAA certification of AM components. Specifically, it focuses on metal AM components fabricated using powder bed fusion (i.e., laser and electron beam) and directed energy deposition (i.e., wire and powder). Along with the authors' collective experience, the report also draws from publicly available information. This paper provides guidance for compliance to 14 CFR 2x.603, 2x.605, 2x.613, 23.2260, 33.15, and 35.17 for metal powder bed fusion (PBF) and directed energy deposition (DED) additive processes. It should be noted that additional guidance may be required for higher criticality parts subject to the FAA rules 14 CFR 23.2240, 14 CFR 2X.571, 14 CFR 33.14, 14 CFR 33.70, and 14 CFR 35.37. Although not comprehensive, this report addresses the following subjects pertinent to AM qualification:

- Development Process
- Supply Chain Qualification
- Material Property Development
- Part Design / Qualification Processes
- Quality Controls

Definitions of commonly used terms are provided in Appendix A.

## 5.2 Overview of AM Component Qualification

As with all new technologies, one of the biggest challenges in certifying AM components for aerospace applications is the general lack of industry data as compared to data available from traditional manufacturing processes. Legacy subtractive manufacturing processes have been improved over the last 70+ years of use. It is therefore, required that the DAH understand Key Process Variables (KPVs) and their impact on the final product. Statistically based material and manufacturing process data SHALL be available at the time of certification.

Some have referred to additive as new and novel, implying that completely new processes should be developed to certify additively manufactured parts. This report recommends the use of well-known material development practices, powder and raw material handling practices, machine operational qualification, process performance qualification, and design qualification that result in a well-grounded aerospace approach to certifying additive parts. This report also provides guidance and suggested methods to design and manufacture AM components in the following areas:

*Development Process*– An initial set of activities need to take place for machine acceptance, installation, and operation. This is needed to lay a foundation for development activities that follow. This phase also includes identification of KPVs, parameter development, initial material testing, material specifications development, post-process development, part process development, and machine operational qualification.

*Supply Chain Qualification*– Process Control Documents (PCDs) SHALL be created and a fixed process established. Process performance qualification is established once all process and part requirements are met.

*Material Properties Development* - Many of the common metallic alloys have their physical, thermal and mechanical properties available in the Metallic Materials Properties Development and Standardization (MMPDS) database or in proprietary material databases that have been developed over decades by Original Equipment Manufacturers (OEMs). To replace these alloys with additively-produced alloys, data substantiating performance of the replacement materials should be provided as dictated by the DAH and regulatory requirements.

*Part Design / Qualification Processes* –Although PBF & DED are relatively new processes for aerospace, the established qualification processes and standards still apply to the final metal product. Being a "new" application of the old, the challenge is to make sure we are applying the processes and standards correctly and completely. A building block approach is recommended to address items such as scale factors, thin-wall conditions, and surface conditions.

*Quality Controls* – Development for stable and repeatable process control needs to be demonstrated the same as with other conventional manufacturing processes. Furthermore, AM may bring a new set of anomalies and/or defects. In some cases, the part geometry is more complex making non-destructive inspection (NDI) techniques challenging. A recommendation is given based on the practices of a long metal part history.

Figure 1 illustrates these five areas of material and process technology maturation and deployment. A new technology such as AM should first demonstrate an appropriate level of technical process maturity which is controlled with specification and process control documents. It should be noted that the sequence of these five areas may occur in a different order than what is presented here, but the guidance given within each of the area is what is most relevant. (Note: Not included here are details surrounding repair and maintenance of AM parts after operational service.)

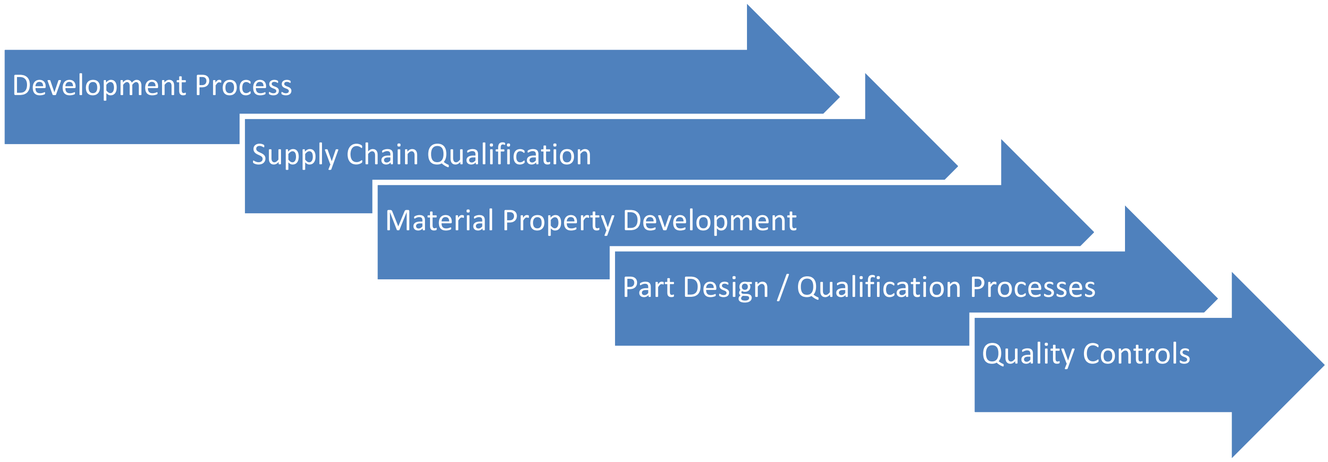

*Figure 1: Additive Development and Qualification Areas*

To support the part qualification effort, material property testing is performed in each of the five areas shown in Figure 1. This may involve a range of test articles, including the additive manufacturing of purpose-built conventional test specimens, specimens with specific features (e.g., as-built surfaces, $K_t$ features, etc.), and specimens excised directly from additively manufactured parts. Material data generation at different stages of the Additive Manufacturing process is shown in Figure 2 below, with additional details provided in the sections referenced in Figure 2: Material Data Generation at Different Stages of the Additive Manufacturing Process.

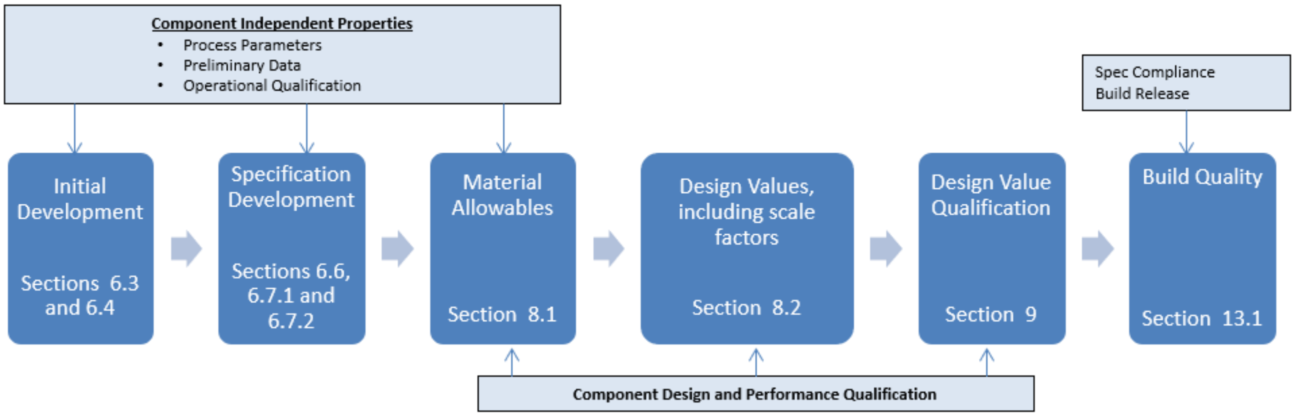

*Figure 2: Material Data Generation at Different Stages of the Additive Manufacturing Process*

# 6 Development Process

## 6.1 Material Development

Additive material development is consistent with other methods of manufacture in that the development process should lead to a controlled microstructure and understanding of the effect of anomalies, which ultimately results in predictable material properties. This allows the additive material to be used reliably in aerospace applications with repeatable performance. Figure 3 is a simple schematic of the well-known material science continuum.

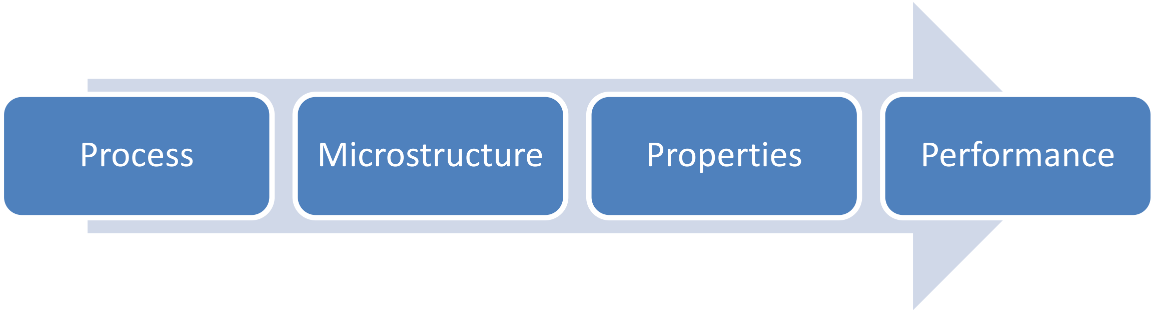

*Figure 3: Materials Science Continuum*

## 6.2 Feedstock Material Specification

Feedstock specifications would typically be alloy-specific with appropriate provisions for various additive processes (i.e., powder bed, wire-fed, or powder-fed) and energy sources (i.e., plasma, electron-beam, or laser).

Powder specification requirements should include, but may not be limited to:

- Chemistry
- Atomization media/method
- Cleanliness, purity
- Particle size distribution and morphology
- Acceptance test requirements
- Lot definitions
- Traceability requirements
- Packaging requirements
- Powder-making process controls

As industry understanding evolves and applications require, powder specifications may also include:

- Entrapped porosity limits
- Powder flow, tap and apparent density, repose angle, and/or spreadability

Wire feedstock material specification requirements should include, but may not be limited to:

- Chemistry
- Melting practice
- Surface condition, including surface quality

- Size and tolerance
- Twist
- Fabrication method
- Lot definition
- Traceability requirements
- Packaging requirements
- Wire-making process controls

Industry standards organizations are actively developing specifications for powder feedstock materials and production processes; some of these relevant to aerospace products are listed below.

- AMS 7001 “Ni Base 625 Super Alloy Powder for Use in Laser Powder Bed Additive Manufacturing Machines”
- AMS 7002 “Process Requirements for Production of Metal Powder Feedstock for use in Laser Powder Bed Additive Manufacturing of Aerospace Parts”
- ASTM F3049 “Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes”

Existing Industry standards organizations specifications for welding wire materials may be appropriate for AM processes, including:

- SAE International Aerospace Material Specifications (e.g. SAE AMS4954)
- American Welding Society specifications (AWS A5.16)

## 6.3 Identify Key Process Variables (KPVs)

To ensure consistent performance, KPVs SHALL be identified, associated tolerance bands determined, and the impact of variation through each tolerance band should be understood. Testing should focus on these KPVs that strongly correlate with desired characteristics of finished part, such as mechanical (e.g., static strength, fatigue, fracture), metallurgical, physical, or chemical properties.

Despite there being many discrete parameters controlling most additive manufacturing processes, the actual number of parameters critically influencing performance is typically a more limited subset. The DAH SHALL demonstrate which parameters, and interactions thereof, are critical to the process (i.e., KPVs) and which are not, and implement appropriate control plans for both.[2] For example, laser power for the hatch may be a KPV, whereas laser power for a contour may not be for a surface that will subsequently be removed.

Two methods may be useful for this purpose (one or both may be used):

- Statistically designed experiments (i.e., a design of experiment (DOE) approach using machine manufacturer input and engineering judgment) may be useful for this purpose. A typical DOE may consist of varying as many as 8 to 10 parameters. Each KPV should be demonstrated to meet requirements throughout the process window (i.e., at the extremes of the parameter settings, considering tolerances) defined within the applicable specification.
- Analysis of material data trends. Coupons are produced using a nominal set of parameters. Statistical analysis (e.g. regression) of coupon data vs. measured (actual) build parameters will

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[2] Aids in identifying KPVs include: AMS7003 (L-PBF), AMS7005 (Plasma Arc DED), AMS7007 (EB-PBF), AMS7010 (Laser Wire DED), AWS D20.1 (Standard for Fabrication of Metal Components using Additive Manufacturing), and MSFC-SPEC-3717 (L-PBF). [AMS7007 is currently in draft form and not publicly available]

identify the KPVs and their effect on material properties. For instance, a series of builds may be produced with a fixed set of commanded parameters. Through use of a power meter, actual power is measured for each build. Coupon testing reveals a correlation between a physical or mechanical property and actual power. Limits for actual power are established going forward to ensure a minimum level of that property.

These parameters are identified as KPVs and fixed such that requalification (full or partial OQ or PQ) is required if one or more of these parameters are changed. The goal of process control is to achieve required consolidation of the feedstock material to consistently produce the component geometry, surface roughness, and microstructures with corresponding properties required for the design intent.

## 6.4 Develop Robust Parameter Set

A parameter set or sets SHALL be developed for each material used and each make/model of machine. A robust parameter set will have all KPVs "centered" in a way that the material properties and part quality are minimally affected due to variation within the control capability of the machine. Parameter optimization is typically achieved through a subsequent DOE focusing only on the KPVs (the insignificant parameters are fixed). One primary goal of parameter optimization is minimizing porosity. Figure 44 illustrates the results of such a DoE.

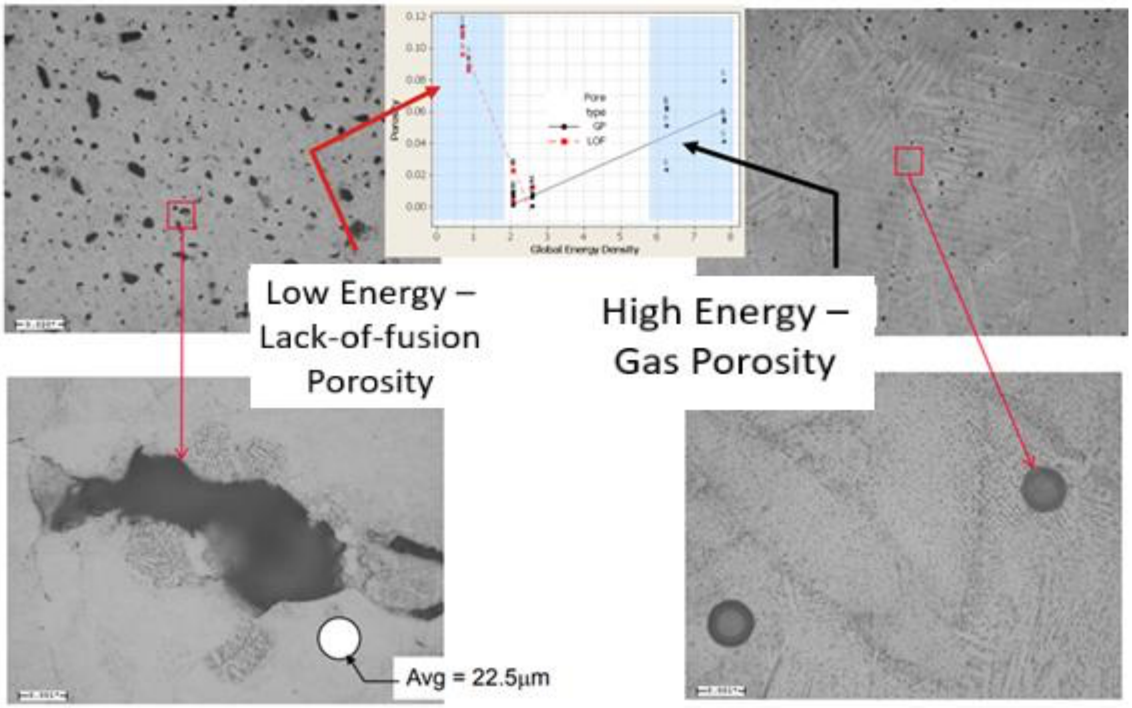

*Figure 4: Global Energy Density Versus Lack-of-Fusion (LOF) & Porosity for L-PBF*

Some DAHs may receive or purchase optimized parameter sets from machine manufacturers or third parties. KPVs SHALL be validated over their ranges to produce consistent material properties on the part producer's specific machine that meet design requirements.

Another process optimization consideration may be minimizing build time. However, the goals of minimizing build time and maximizing material density (i.e., minimizing gas porosity and lack-of-fusion) are conflicting and hence a series of DOEs may be executed to optimize part density and build speed.

## 6.5 Develop Post-processing

Most materials require some post-build processing to be useful. Processing may include powder removal, support removal, machining, surface enhancement, and/or thermal treatment.

Post-processing is a broad term used for any process which occurs after the additive “printing” process is complete.

### 6.5.1 Powder Removal

For powder-based technologies, powder removal may be required, especially for parts with internal features. Part designs and part orientation during the build process should be defined up front, such that removal of unfused powder can be accomplished. Methods to remove powder range from manual application of compressed air to automated systems that manipulate and vibrate parts while still on the build-plate, or in a blasting cabinet for electron beam powder bed fusion (EB-PBF). Subsequent powder removal methods may include processes similar to those applied to lubrication system components (i.e., solvent flush) with subsequent “patch testing” (i.e., inspection of paper filters subjected to effluent). Unfused powder should be removed prior to subsequent thermal processes, or it becomes impossible to remove as it may sinter and adhere to part surfaces.

### 6.5.2 Stress Relief

During the build process, significant residual stresses can develop in the part, resulting in warpage (or, in extreme cases, cracking) if a stress relief heat treatment is not performed. While commercial tools have been developed to predict and manage these residual stresses, a stress relief thermal treatment is usually unavoidable. Stress relief is typically required after laser powder bed fusion (L-PBF) and DED. In the case of L-PBF, this is typically performed prior to removal of parts from the build plate. Note that if appropriate, the stress relief heat treatment may be combined with other heat treatment process steps to optimize microstructure and/or minimize the number of subsequent processing steps.

### 6.5.3 Removal from the Build Plate and Support Removal

Typical build plate removal processes include Electro-Discharge Machining (EDM), water-jet cutting, or band-saw cutting. If support features are used, their impact on local stress concentration or microstructure SHALL be accounted for. Typical support structure removal methods include use of hand tools, conventional machining, mass finishing, non-conventional machining (including EDM, ECM, or water-jet) and chemical removal via dissolution. The impact of these processes on subsequent surface integrity SHALL be understood.

### 6.5.4 Hot Isostatic Pressing (HIP)

HIP has been shown to be effective to minimize porosity (including lack-of-fusion porosity) when the porosity is not surface-connected. It may also serve to homogenize localized chemical segregation. Further, advancements in the design of HIP vessels have enabled effective solution heat treatment via fast cooling capabilities. However, even though HIP requires high purity gas as a pressing medium, even typical trace impurities (for example, oxygen, nitrogen, hydrocarbons, moisture, etc.) may be present in significant quantities given the high-pressure nature of the process. The impact of these impurities and resultant contamination should be understood if HIP surfaces exist in finished parts. It should be noted that HIP may not be fully effective in addressing all types of defects, and its effectiveness SHALL be validated for a specific type of material anomaly.

#### 6.5.5 Heat Treatment

Additional heat treatments may be required to develop final part microstructure (including reduction of anisotropy) and resultant mechanical properties. Heat treatments for traditionally produced alloys may not be appropriate for AM versions of the same alloy. For instance, application of typical solution heat treatment cycles used for cast aluminum alloys have revealed extensive hydrogen "bubbles" in AlSi10Mg.[3] Also, direct aging of powder bed fusion Alloy 718 has revealed formation of extensive Laves phases, known to be detrimental to the strength and fatigue properties of Alloy 718.[4]

#### 6.5.6 Surface Enhancement

Current powder bed technology is limited to achieving surface roughness values no finer than 200 u-in Ra. Conventional surface finishing processes may be applied to improve the surface roughness to perform required inspections and achieve design-required surface roughness and material properties. For example, glass bead blasting, simple hand finishing, or alternate methods (including chemical and electro-chemical processes) have been shown to improve as-produced surface conditions to sufficiently facilitate penetrant inspection. Wire-fed technologies yield surfaces that should be machined to yield useful properties. Care should be taken to prevent obscuring of anomalies when surface enhancements are used prior to surface inspection.

#### 6.5.7 Other Common Post-Processing Techniques

Other common post-processes include machining, joining (e.g., welding, brazing), chemical processing, coating, etc. In general, processes applicable to traditional materials also generally applicable to AM materials.

### 6.6 Preliminary Property Determination

Preliminary mechanical property determination is likely to be performed during process development, which then serves as a foundation for subsequent extensive characterization (see Section 8). However, a logical stepping stone toward that end is development of material specification minimum mechanical properties. This is, at a minimum, room temperature static tensile properties (i.e., 0.2% yield strength, ultimate tensile strength, and elongation). The statistical basis of this data set should be determined by the accepted industry or DAH material development practice (e.g., number of samples, number of lots). One example of an accepted industry practice is a minimum of thirty observations per specified orientation, consistent with MMPDS Chapter 9 guidelines, but adapted for AM-specific concerns[5]. Recognizing the materials science continuum (Figure 33), this may also include quantifying proxies for strength, like grain size.

### 6.7 Release Part material and Fusion Process Specifications

Part material and fusion process specifications for an additively manufactured material SHALL include the requirements to ensure this material has the required strength and other properties assumed in the design data.

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[3] "Formation and reduction of hydrogen porosity during selective laser melting of AlSi10Mg", C. Weingarten et al. / Journal of Materials Processing Technology 221 (2015) 112–120

[4] "The influence of Laves phases on the high-cycle fatigue behavior of laser additive manufactured Inconel 718," Shang Sui et al., Materials Science & Engineering A 695 (2017) 6–13.

[5] GAAM-M18A, "SAE AMS AM Metals General Agreement Data Submission Guidelines (for Additive Manufactured Metals)", Initial Release (4/5/2018).

### 6.7.1 Part Material Specification

A typical part material specification would be specific to an alloy, additive process, and thermal treatments. A typical part material specification consists of controls around the following:

- Feedstock material specification.
- Material fusion process specification.
- Chemistry – typically based on the limits established by the feedstock specification with considerations for constituents that might change in concentration as a result of fusion.
- Thermal treatment – thermal treatments required to meet mechanical properties
- Metallography – typically would control general microstructure and grain size
- Anomaly types and limits.
- Mechanical properties – at a minimum, room temperature tensile properties.

### 6.7.2 Process Specification

A process specification would typically be additive process-specific and material-agnostic. The process specification and supporting process control documents (PCDs) are generally in five categories as shown below and detailed in Section 7.2 “Process Control Documents”.

- Infrastructure
- Machine Qualification Plans
- Feedstock Control Plan
- Part Production Plans
- Post-process Plans

Industry standards organizations have been active in developing specifications for fusion and deposition processes; some of these relevant to aerospace products are listed below.

- AMS 7003, “Laser Powder Bed Fusion Process”
- AMS 7005, “Wire Fed Plasma Arc Directed Energy Deposition Additive Manufacturing Process”
- AWS D20.1, “Standard for Fabrication of Metal Components using Additive Manufacturing”

## 6.8 Part Process Development

Part process development is required to ensure all design and business requirements can be met for the part. Additive part development requires a very close concurrent working relationship between design engineering, materials engineering, and the supply chain organization. The following items are included as part of this development process:

### 6.8.1 Manufacturing Model Compensation

Geometry “corrections” are applied, as required, to the engineering model to yield a manufacturing model that accounts for thermal distortion and build overhang distortions, with the intent of meeting the design requirements. This is most often accomplished using distortion modelling tools and a series of build trials.

### 6.8.2 Support Structure

Support structure is material added to the manufacturing model to provide part support and restraint during the build process and post processes. Support structure may also aid in heat transfer during part fabrication. A typical area requiring support structure is a part overhang which is below 45 degrees with respect to the build plate and is not self-supporting during the build.

### 6.8.3 Orientation and Platform Position

Part layout on the build platform should be optimized to meet both design and business requirements. For example, minimizing supports and maximizing the number of parts on a platform generally will reduce the manufacturing cost per part. However, special attention is required to ensure consistency in meeting design requirements throughout the build volume.

## 6.9 Machine Acceptance

Metal additive machines are manufactured for a broad market. For aerospace use of this equipment, the part producer SHALL qualify the machine in a way that demonstrates the appropriate level of performance under defined process controls. The required machine qualification follows the well-known approach of Factory Acceptance Test (FAT), Installation Qualification (IQ), Operational Qualification (OQ), and Performance Qualification (PQ).

### 6.9.1 Machine Factory Acceptance Test (FAT)

The FAT is performed at the equipment manufacturer prior to shipment. FAT should ideally include all the machine related data that are a part of the documentation showing a machine's fitness for manufacturing, including evidence that the machine meets the purchaser's procurement specification. The FAT results should be requested by the part producer and maintained as a permanent record. The FAT may be witnessed by a representative of the purchaser.

### 6.9.2 Machine Installation Qualification (IQ)

Upon delivery, objective evidence is produced to show that all key aspects of the process equipment and ancillary system installation adhere to the part producer's specification and that the recommendations of the supplier of the equipment are suitably considered.

IQ starts with machine set-up, initial calibration, and a site acceptance test (SAT). To validate that each machine is performing to a minimum standard, the part producer will use a SAT to accept delivery of a new machine. The SAT build is an equipment manufacturer standard build or jointly agreed to by both the equipment manufacturer and the part producer. This often involves the need for repeated trials until SAT requirements are met. The results between the FAT, site acceptance/IQ for a given machine should be consistent. Any variations should be investigated and corrected.

### 6.9.3 Machine Operational Qualification (OQ)

OQ is to be performed under sufficient process control to maintain stable material performance. Process control includes machine calibration and preventative maintenance. Operational Qualification (OQ), Machine OQ, and machine qualification are used within the context of this report to have the same meaning. Machine OQ occurs when the machine is qualified to a given material specification. These controls will become PCDs as part of the PQ.

The part producer SHALL run a series of metallurgical, mechanical, and physical property tests to ensure the machine meets their material specification. Material DOE to determine acceptable performance throughout the tolerance range of KPVs is part of the testing. Standard OQ builds SHALL demonstrate material performance and may include artifacts[6] to validate other metallurgical,

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[6] "Proposal for a standardized test artifact for additive manufacturing machines and processes," Moylan et.al. Proceedings of the 23rd Intl. Solid Free Form Symp.–An Additive Manufacturing Conf., Austin, TX, USA, August 2012, pp. 902-920).

dimensional, and surface roughness characteristics.

OQ has been completed when it has been demonstrated that the material specification requirements can be met by the machine with statistical relevance over multiple builds.

### 6.9.4 Process Performance Qualification (PQ)

PQ has occurred when it has been demonstrated all product requirements are met, under process control, and can be produced by with statistical relevance over multiple builds in a production environment. PQ is further discussed in Section 7.3.

## 7 Supply Chain Qualification

Additive manufacturing part producers, whether internal or external, require qualification by the DAH. The part producer may be provided complete part and process requirements, or the part producer may develop the process requirements to meet the part requirement. All part producer quality organizations are responsible to meet the qualification requirements.

The FAA document, "Job Aid for Evaluating Additive Manufacturing at an MRO" may be a useful reference and is available on the **Flight Standards Information Management System** FAA web site

Prior to the supply chain qualification for additive manufacturing, other industry certification should be completed. Common certifications include ISO 9001, AS 9100, and NADCAP.

### 7.1 Supply Chain Qualification Flowchart

Figure 5 illustrates the buyer requirement flow-down to the part producer and subsequent supply chain process flow.

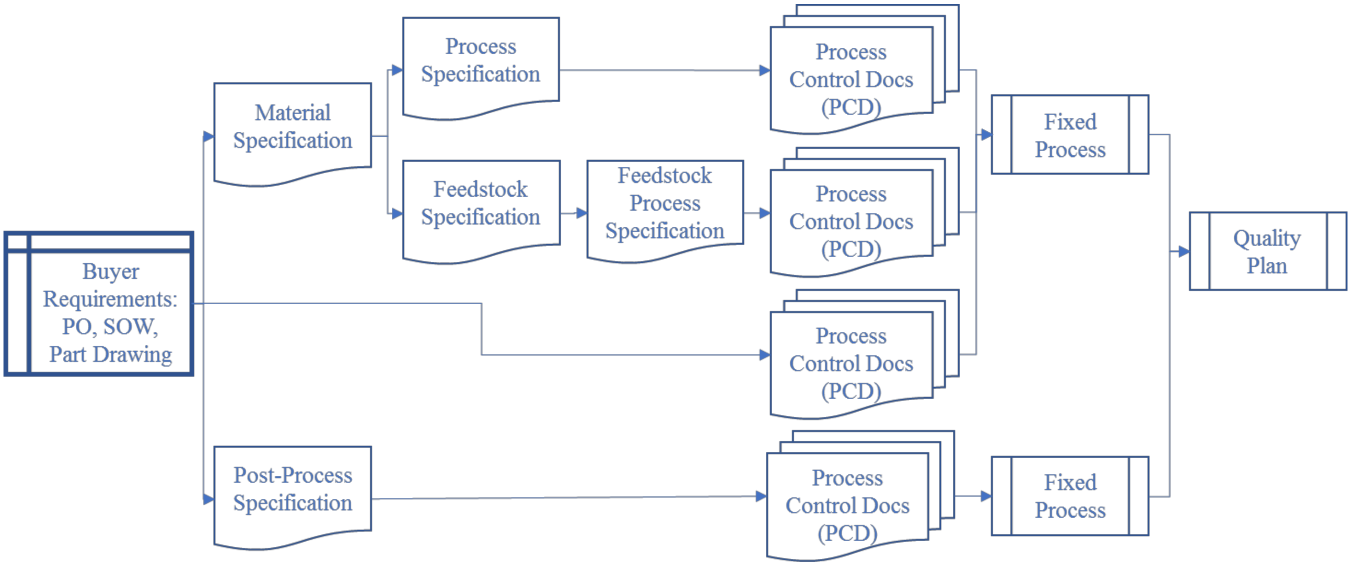

*Figure 5: Supply Chain Qualification Flowchart*

### 7.2 Process Control Documents (PCD)

This section describes the principal requirements that need be established and demonstrated by the part producer to maintain process control of additively manufactured products.

The PCDs SHALL be established by the part producer based on the requirements of the DAH part specification, process specification, and drawing. Once the process is qualified, the PCDs are fixed and any changes to the PCD, with a potential impact to a KPV, SHALL require re-qualification prior to the change being implemented into production. PCDs are typically defined for manufacturing processes which require process control to maintain stability to product requirements, or additional DAH requirements such as design values.

Post-process operations that cannot be sufficiently controlled by part drawings and specifications should be controlled by a PCD.

(The following are examples of Process Control Documents)

- Infrastructure
    - Facility Control Plan
    - Operator Training and Qualification Plan
    - Work Instruction Plan
    - Software Configuration Control Plan
- Machine Qualification Plans
    - Key Process Variable (KPV) Plan
    - Machine Configuration Plan
    - Preventative Maintenance Plan
    - Machine Calibration Plan
    - Machine Requalification Plan
- Feedstock Control Plan
    - Feedstock Lot Control Plan
    - Feedstock Handling Plan
    - Powder Feedstock Re-use Plan
    - Machine and Material Alloy Change Contamination Avoidance Plan
- Part Production Plans
    - Engineering Requirements Plan
    - Manufacturing Part Definition Plan
    - Machine Parameters Plan
    - Build Interruption Plan
    - Quality Control Plan
    - In-Process Monitoring Inspection Plan
    - Record Keeping Plan
- Post-Process Plans
    - Powder Removal Plan
    - Stress Relief Plan
    - Hot Isostatic Press (HIP) Plan
    - Heat Treatment Plan
    - Build Plate Removal Plan
    - Support Removal Plan
    - Surface Enhancement Plan

### 7.2.1 Infrastructure Control Plans

Infrastructure control plans define the facility control, operator training and qualification, work instructions, and digital thread change management requirements.

#### *7.2.1.1 Facility Control Plan*

The part producer should have a defined and documented set of requirements for measuring and controlling temperature, humidity, process gasses, air, power stability (including back up power), vibration, electro-magnetic interference (EMI), handling, movement and storage of powder, general cleanliness, positive tool control, personal protection equipment (PPE), industrial health and safety (IHS), and ergonomics. However, it should be noted that each producer may have different standards defined for the aforesaid that may be used for controlling their respective facilities.

#### *7.2.1.2 Operator Training and Qualification Plan*

Training and qualification requirements of the operators are defined to ensure their ability to manufacture components to acceptable standards. Training and qualification of an operator SHALL be specific to an equipment manufacturer make and model. Additional training and qualifications are required for each machine that is of a different make and model. Qualification of operators SHALL include: training and retraining at prescribed intervals; practical examinations and build demonstrations. Note that changes to machine software versions may require partial requalification of the operator. It is recommended that the training program should at a minimum, include the following topics:

- Raw material (feedstock such as powder or wire) storage and safety
- Raw material handling
- Preventative maintenance
- In process steps for machine and component cleaning
- Machine calibrations
- Environmental controls
- Build file and machine parameters setup
- Running and recording build information
- Build cycle interruptions
- Understanding and recognizing build defects
- Removing components from machine, build plates and post-processing as appropriate
- Safety precautions to be observed

Ongoing training, as processes and procedures are developed, should be developed internally and cover all aspects of routine operation, maintenance, quality control, etc. Examples of training curricula can be found in AMS 7003 and MSFC-SPEC-3717.

#### *7.2.1.3 Work Instruction Plan*

All manufacturing operations for flight products SHALL have written work instructions approved by the organization defined by each part producer.

#### *7.2.1.4 Software Configuration Control Plan*

All the electronic files needed to make a part from an approved design SHALL be maintained with no loss of integrity. A methodology for verifying the integrity of part models throughout all stages of the digital part definition associated with the process SHALL be documented. This should be verified by the producer via a digital control plan that provides a method for tracking the digital files. The digital control plan SHALL at a minimum include:

- Name and revision level of individual computer aided design (CAD) files
- Slicing, build layout and build parameter files; software revision levels of the associated firmware and hardware.
- Software revisions

Configuration management of the digital files defining the parts, build geometry, parameters, and records of the build is critical to producing consistent parts. Files requiring control are shown in Figure 6.

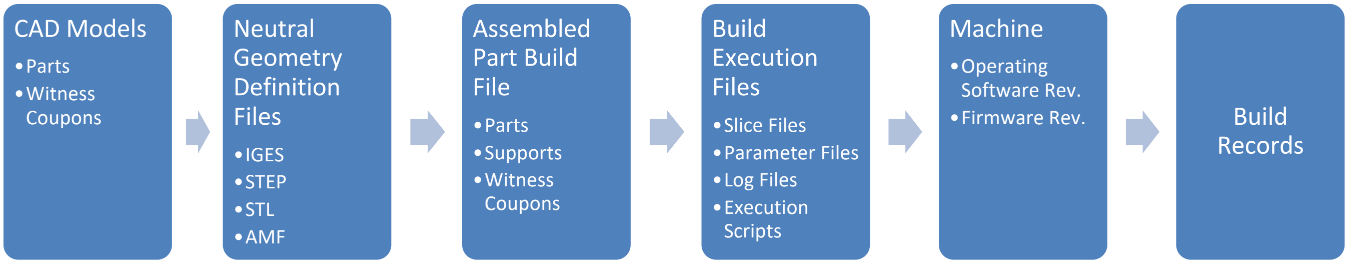

*Figure 6: Software Requiring a Control Plan*

### 7.2.2 Machine Qualification Plans

#### *7.2.2.1 Key Process Variable (KPV) Plan*

KPVs SHALL be determined though DOE or similar approach. The allowable range of values are used to define tolerance values. The tolerances should be shown to not impact the requirements in an unacceptable way.

#### *7.2.2.2 Machine Configuration Plan*

All machines used for production and certification purposes SHALL complete a PQ. The machine configuration SHALL be fixed once qualified. Machine configuration includes the machine hardware (make, model, and serial number) and software defined by both the machine OEM and the part producer.

#### *7.2.2.3 Preventative Maintenance Plan*

All machines used for production and certification purposes SHALL have an approved, documented and tracked preventive maintenance plan/schedule. Aerospace parts will likely require a supplemental plan beyond the equipment manufacturers recommended maintenance plan.

#### *7.2.2.4 Machine Calibration Plan*

Machine calibration plan is defined by the part producer with KPVs required to establish a stable and repeatable process. Note that calibration requires the use of certified standards to verify any measurements made during the calibration process. KPVs SHALL be defined by the part producer. An example minimum set calibration items for L-PBF would include the following KPVs[7]:

- Build platform position
- Focal length
- Shielding gas flow rate
- Layer thickness
- Power of each laser
- Hatch/Contour spacing & overlap
- Beam spot size and shape of each laser
- Beam quality/stability of each laser
- Scan speed

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[7] SAE AMS Additive Manufacturing process specifications provide industry accepted examples of calibration and verification plans for other additive manufacturing processes.

#### *7.2.2.5 Machine Requalification Plan*

Machine requalification SHALL be performed when any of the following events are experienced in a given machine:

- Updates to software, firmware, or build execution files which could potentially impact a KPV (reference Figure 5).
- Replacement, repair, or alteration of any component that can affect a KPV
- Moving the machine
- Changes to the machine set-up or configuration within the facility

Re-establishing qualification following any event which negates its active qualification status may be accomplished through at least the following:

- Verifying that the event negating active qualification is resolved
- Verifying the machine is in a calibrated state with calibrations re-performed as necessary
- Successfully evaluating the process using standard OQ build verification requirements (as described in Section 6.9.3).

### 7.2.3 Feedstock Control Plans

As-received raw material documentation SHALL include certificates of conformance and any applicable additional specifications depending on the method of manufacture of the raw material (powder or wire feedstock).

#### *7.2.3.1 Feedstock Lot Control Plan*

Traceability SHALL be maintained for feedstock used for both certification and production. If lot blending or compositional changes have occurred as with re-use of powder, a traceable history SHALL be maintained.

#### *7.2.3.2 Feedstock Handling Plan*

Process control document SHALL have a feedstock quality control audit plan to verify fitness for use. Powder handling and equipment SHALL not cause contamination or cross contamination. Powder handling and usage, including sieving, blending, and recycling of powder SHALL be controlled. Feedstock requirements are determined by demonstration that final part requirements are met throughout the entire acceptable feedstock specification range.

Storage requirements should include the acceptable range for humidity and temperature.

#### *7.2.3.3 Powder Feedstock Re-use Plan*

During the development of the feedstock specification reuse should be considered. Specification tolerance should be defined such that full component requirements are met with new and re-used powder. Reused feedstock SHALL meet the requirements of the feedstock material specification. Additional requirements for used powder (e.g., blending, limits, handling and storage) SHALL be defined in a PCD.

Re-use metrics and limits SHALL be established to ensure, at the limiting state of reuse, OQ & PQ requirements are met:

- The effects of reuse on material performance are demonstrated to meet part material requirements

- The effects of reuse on part dimensions are demonstrated to meet part requirements
- The effects of reuse on part function are demonstrated to meet part requirements

#### *7.2.3.4 Machine and Material Alloy Change Contamination Avoidance Plan*

Prior to introducing a change in powder composition to a machine, a deep clean process should be executed to ensure removal of all residual powder from machine surfaces exposed to powder.

For powder bed machines, cross contamination of different powder compositions, within a machine or between machines, SHALL be mitigated. Adjacent machines using different powder compositions should be physically separated or otherwise sufficiently isolated to avoid cross contamination. Contaminated feedstock powder and/or machine SHALL be dispositioned through the Material Review Board (MRB) process.

### 7.2.4 Part Production Plans

#### *7.2.4.1 Engineering Requirements Plan*

It is common that certain engineering requirements be maintained for those properties that cannot be adequately controlled through drawing, CAD files and specifications. An example would be the demonstration that the manufactured part meets the applicable design values at all locations, as defined by the DAH.

#### *7.2.4.2 Manufacturing Part Definition Plan*

Manufacturing part definition, such as a CAD model containing support structure and distortion compensation, SHALL be configuration controlled and traceably linked to each part.

#### *7.2.4.3 Machine Parameters Plan*

Each part may require a unique set of machine parameters. The parameter set used SHALL be configuration controlled and traceably linked to each part.

#### *7.2.4.4 Build Interruption Plan:*

Planned build interruptions may be allowed, but the restart procedure SHALL be included in an approved PCD. An unplanned build interruption SHALL be dispositioned in an MRB review. MRB considerations should include, but not limited to, the following:

- The effects of interruption on material performance are demonstrated to meet part material requirements
- The effects of interruption on part dimensions are demonstrated to meet part requirements
- The effects of interruption on part function are demonstrated to meet part requirements

MRB review is required for build interruptions that exceed the PCD allowance.

#### *7.2.4.5 Quality Control Plan*

The elements of the quality plan requiring process control SHALL be maintained as part of a PCD.

Refer to Section 0 for discussion on quality control.

#### *7.2.4.6 In-Process Monitoring Inspection Plan*

In-Process Monitoring Technologies associated with additive manufacturing processes are developing at a rapid pace. As for all manufacturing processes, process feedback can be a valuable tool. Such a capability will certainly reduce development time and cost, as well as improve product yield. These systems should not be confused with the full quality control plan, which includes final product validation.

Reference Section 14.4 for discussion on in-process monitoring used for part inspection.

#### *7.2.4.7 Record Keeping Plan*

Identification of AM components SHALL be maintained such that the component can be traced to the records package. The final records package for all components manufactured with AM should include at a minimum:

- Reference to engineering drawings, specifications, and CAD file revisions
- PCD revisions
- Feedstock lot, and certification
- Part fabrication records, to including:
    - Machine-generated build reports
    - Planned Build Interruptions
    - Unplanned Build Interruptions
    - In-Process Rework
    - Post-Processing Variables
    - Inspection Records
    - AM Machine Operator Qualification Records
    - Calibration Control Plan
    - Digital Control Plan
    - MRB Items
- Machine qualification records, to including:
    - FAT
    - IQ
    - OQ
    - PQ
    - Maintenance & Calibration

### 7.2.5 Post-Process Plans

Common post-processes that require control in PCDs include.

- Powder Removal Plan
- Stress Relief Plan
- Hot Isostatic Press (HIP) Plan
- Heat Treatment Plan
- Build Plate Removal Plan
- Support Removal Plan
- Surface Enhancement Plan
- Other Special Process Plan

## 7.3 Process Performance Qualification (PQ)

The various levels of machine qualification (IQ, OQ, and PQ) are discussed in Section 6.9.

PQ is established after demonstrating conformity to specifications, PCDs, and the successful completion of first article inspection with statistical (e.g., 3 sigma capability) relevance over multiple builds. Performance Qualification (PQ), process PQ, and process qualification are used within the context of this report to have the same meaning.  Process PQ occurs when the process is qualified to the component requirements.  The process is fixed once PQ is complete.

Each machine serial number SHALL be qualified independently.  The PQ SHALL be under a fixed process defined and implemented by the PCDs.

### 7.3.1 Re-establishing Performance Qualification (PQ)

Qualification requirements are defined within a PCD.  Any change that requires machine requalification (see 7.2.2.5), or that can affect PQ requirements, SHALL necessitate re-establishing PQ.

The basis of successfully re-establishing PQ may include elements of OQ and PQ performance requirements as defined by an applicable PCDs.

### 7.3.2 Qualification of Multiple Machines.

When more than one machine is required to meet production demand for a part, some qualification efficiency is possible.  It SHALL be assured that all machines have successfully completed the full PQ. Efficiency may occur in that the qualification of each machine after the first by using the PCDs established by the first machine. Machine equivalency is established when the null hypothesis (H0), which assumes that a machine is different than the performance standard (e.g. material spec, allowable, or design value), is rejected, based on statistical comparison of data from the candidate machine with the approved performance standard.

## MATERIAL PROPERTY DEVELOPMENT

### 8 Material Allowables and Design Values Development

Material allowables and design values are needed by the design engineering and analysis staff to enable practical and cost-effective qualification approaches for application of these technologies to aerospace applications. Material allowables and design values provide the basis for static, fatigue and damage tolerance analysis methodologies utilized during the design qualification. The rigor in material property development may be influenced by the part requirements, criticality and overall risk associated with the parts usage.

It should be noted that material allowables and design values, while closely connected, are two different notions as defined in the Appendix. While material allowable addresses bulk material properties, the design values account for impact of part specific features, surface finish and other factors.

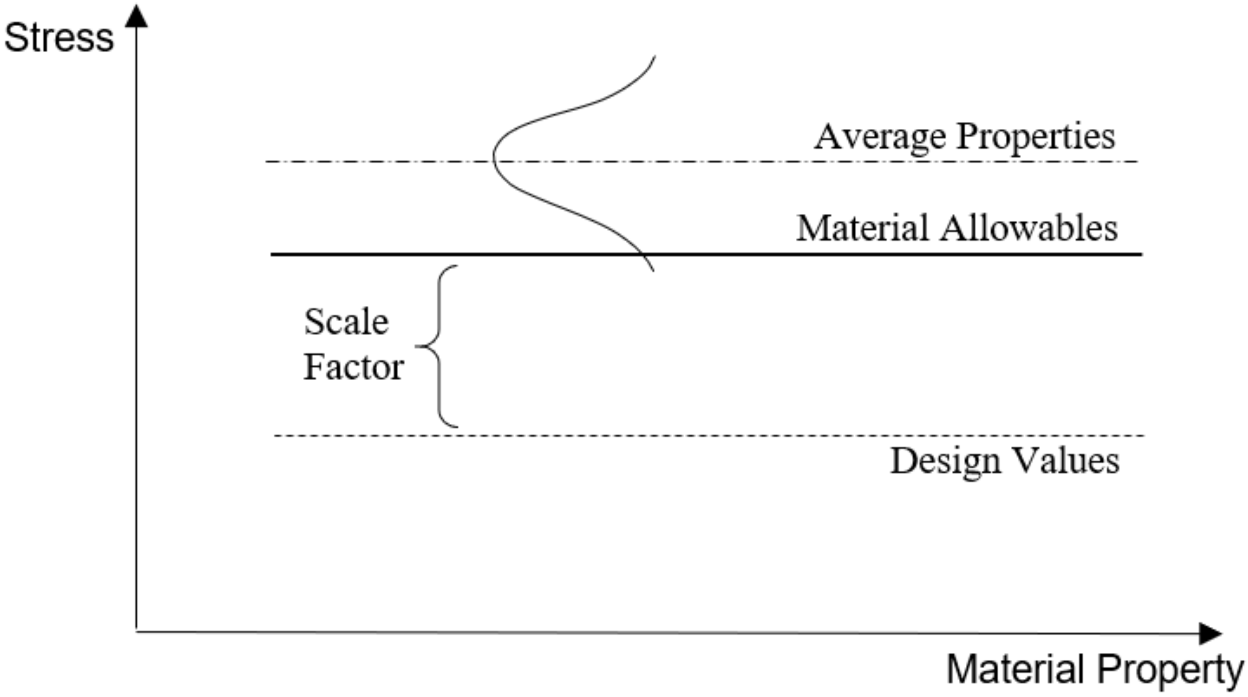

Figure 7 illustrates this approach.

The generation of data from simple individual separately built coupons or even specimens extracted from parts may not fully represent local variations in properties for parts. Therefore, the applicability and fitness of use of bulk material allowables and design values SHALL be demonstrated for each individual component.

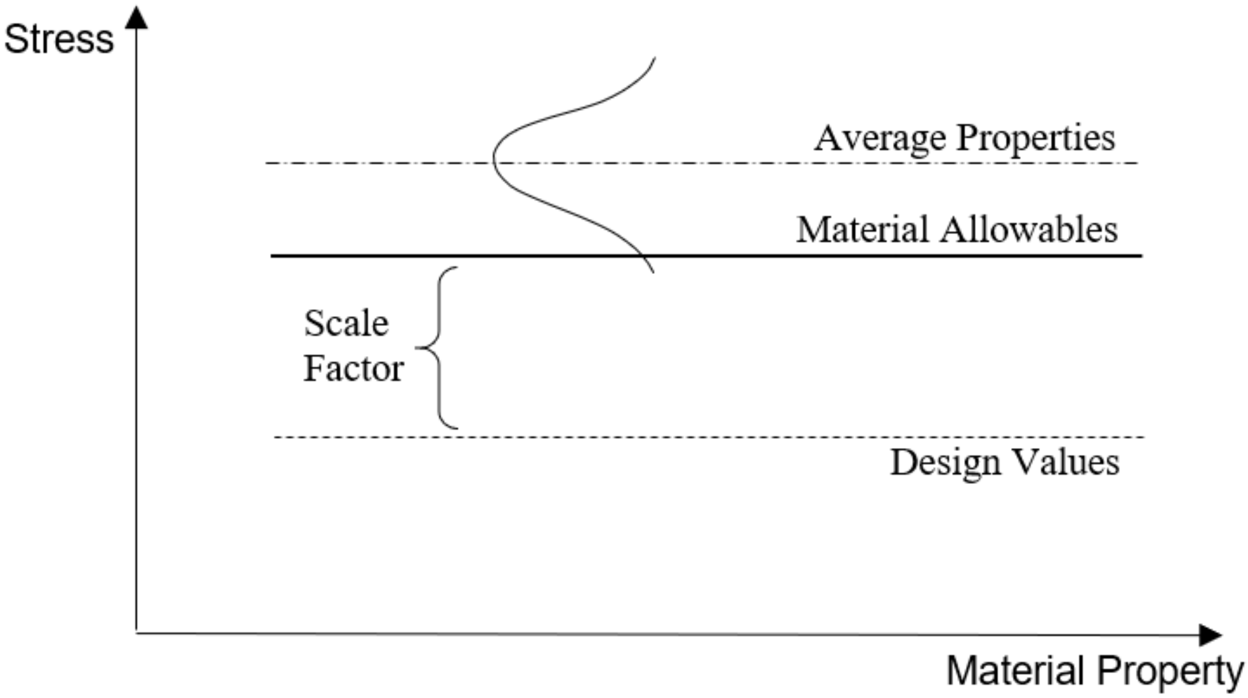

*Figure 7 – Material Allowables versus Design Values*

The foundation for material allowable and design values is to fully encompass all the variables that influence the resulting performance in the intended application. When establishing material allowables and design values, the entire additive manufacturing process for part fabrication, including feedstock, deposition processes and post-processing SHALL be taken into account.

Definitions of commonly used terms, such as material allowables and design values, and their range of applicability, are provided in Appendix A. These definitions apply to material allowables and design values for static strength analysis and may be different for values used in fatigue and damage tolerance analysis. All material allowables SHALL meet the regulatory requirements (e.g., engines, propellers, aircraft), internal quality standards and part criticality level.

It should be noted that material allowables and design values always have applicability limitations based upon the extent of process and design space coverage represented by the material allowables test data. Such limits should be clearly defined in the material allowables and design values documentation. Examples of such limits include operating temperature, maximum temperature exposure, applicable material specification, machine build parameters, surface condition, etc.

The following sections in this chapter outline the overall process for generating material allowables and design values using different levels in the building block approach (see Figure 8). Material allowables are addressed in Section 8.1, and design values in Section 8.2.

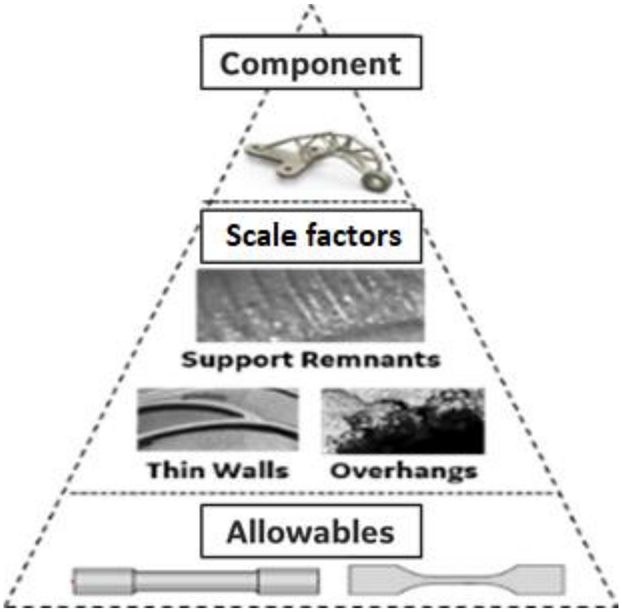

*Figure 8- Building Block Tests for Design Values*

## 8.1 Material Allowables Development

A prerequisite for generating material allowables is the development of a repeatable and robust manufacturing process system defined by approved material and process specifications. Preliminary property data may be created once OQ (See Section 6.9.3) has been completed. Key property data critical to part performance SHALL be statistically demonstrated from every machine after PQ (See Section 7.3).

Material allowables are the most commonly applied basis for design and structural analysis across the industry for all manufacturing methods including additive. The material allowables in this case will either be part of an approved public or proprietary database or developed at the time of need. It is unusual for a full coverage material allowable data set to be generated for initial implementation. It is more likely that material allowable and design values are developed for a specific design application and then expanded.

Sources of variation that may contribute to material variability and that SHALL be evaluated include, but are not limited to the following:

- Feedstock material lot to lot
- Build cycle to build cycle
- Machine to machine
- Heat treatment lot
- Effect of microstructure differences occurring spatially throughout a build due to thermal history, scan or deposition strategy, or inter-pass temperature, etc. (i.e., location in build volume).
- Process drift of KPVs at limit of tolerance band (local)

A test matrix should be defined considering all relevant sources of variation, including those defined above. The interactions among these variations should also be accounted for (e.g., chemistry interaction with energy input). Specimen pedigree, including feedstock, process, location and orientation traceability (e.g. production component traceability), SHALL be documented. Possible test strategies include, but are not limited to:

- Feedstock and processing variability are often best captured by test of specimens fabricated from an appropriate sample of material lots and build jobs.
- Effect of process parameters are often best captured through a Design of Experiments approach to establish acceptable parameter ranges.
- Evaluation of directionality of material properties is best captured by test of coupons orientated in various directions relative to the build volume (e.g., x, y, z). The resulting design values will be determined to be either isotropic or directionally dependent.

Statistically based material allowables are developed using coupons that are either purpose-built or excised from pre-production components or generic shapes.

All relevant build directions and features that use the same machine parameters/thermal history should be considered. The approach of coupon extraction from configured parts is feasible for thicker parts with relatively simple or traditional machined part geometries. However, extraction of test coupons from parts with complex or thin walled geometries may be difficult and may drive the need for purpose-built industry standard coupons and test methods. In some circumstances, there may be a need for new coupon configurations and specialized test methods.

## 8.2 Design Value Development

The DAH SHALL define and account for all known sources of potential variation from material allowables in the development of design values. It is industry practice to use the bulk material allowable data to develop design values. The part specific features are tested separately to create scale factors for use within the structural analysis. Sources of variation that may contribute to a difference in part performance and the material allowables include, but are not limited to the following:

- Environmental factors
- Effect of non-standard test specimen geometry (i.e., small test specimens may be necessary to evaluate actual part material)
- Effect of surface roughness, both as-built and improved, on material performance as applicable.
- Powder reuse (see Section 7.2.3.3). The effects of reuse on material performance SHALL be either substantiated as negligible or material property data representing the limiting reuse state are incorporated directly into the material property test program.

The development of design values data SHALL account for any geometric feature, location in the part or post-processing that may result in design values that differ from the part material allowables (bulk material) properties. This may involve testing at the element, subcomponent, or component level. KPVs used to build elements, subcomponents, or components should be the same as for the part they represent. Examples of features or locations in parts that may have unique design values include, but are not limited to:

- Thin wall section which deviates in material performance from the material allowable
- Any feature, complex part geometry, location or orientation where the microstructure, anomaly distributions or mechanical properties vary from the bulk material characteristics
- Holes, overhangs, and bridge features
- Substrate plate if included in the final part and is exposed to thermal treatments outside of the original material specification.
- Substrate plate to deposition interface heat affected zone if this interface is included in the final

part geometry.

- Existing part to deposition interface for DED processes if the deposition is applied directly to an existing part.
- Intersection of deposition paths in a DED build.
- Interface of the part and support structure. (May result in local stress concentrations or microstructural change).

### 8.2.1 Part Specific Material Allowables and Design Values

Part specific material allowables and part specific design values, which account for part features, may only be applicable to one set of fixed process and controls (i.e., one specific machine type, feedstock, process and post-process) for fabrication by one specific part producer. Although these design values are part number specific, they can be expanded upon, forming the basis for the development of material allowables with a broader application space. Expanded applicability may be achieved by a statistical equivalency/buy-in approach. This could be achieved by pooling test data which reflects additional part designs and features, environmental factors, as well as revisions to material and process parameters.

### 8.2.2 Part Family Material Allowables and Design Values

Development of material allowables and/or design values may also take advantage of the fact many parts are fabricated using identical feedstock and process parameters. A part family may be established by defining the key characteristics (e.g., geometric features, feedstock, and processing window), and developing design values representative of the part family features and criticality. The resulting design values would then be applicable to any part defined to be within that family. This approach is more efficient than creating unique allowables and design values for every part.

Use of a part family approach still requires the same OQ of the material. This means for instance that they SHALL have the same:

- Feedstock material specification including grade and class of the feedstock, if applicable.
- AM process specification.
- Part material specification.
- PCD, with the exception of different part geometry.
- additive material post processing (e.g. post-processing such as thermal treatments).

If using existing material allowables and part design values, the same PQ SHALL be used to qualify the material including statistical equivalency (see Section 7.3.2) to the existing approved additive mechanical properties including design value scale factors (e.g., fatigue with surface roughness and thin wall).

## PART DESIGN / QUALIFICATION PROCESSES

## 9 Design Value Qualification

As highlighted in Section 8.1, material allowables are established for a material/machine/parameter set. These material allowables allow the design engineer to select the appropriate material and material properties to use in developing part designs.

Finally, the consistency between the scale factor developed (see Section 8.2) and the unique design value of the part to be qualified SHALL be verified.

### 9.1 Design Value Verification

Part specific material allowables are generated using one set of fixed process variables for fabrication by one specific part producer (see Section 8.)

If separately built test specimens are used to develop part specific design values, the DAH needs to demonstrate that the test specimens accurately represent the properties of the finished part. These specimens need to use the same feedstock specification, AM process specification, PCD (including KPV settings and values), and post-processing including thermal treatments, machining, and surface enhancements as the part being certified. Separately built specimens used to develop part specific design values should have the same attributes as the parts they represent including but not limited to surface conditions, similar anomaly levels, microstructure, and hardness.

## 10 Detailed Design Qualification

Prior to a part being released for manufacture, the design SHALL be approved or qualified for production. This approval should be the result of an iterative development process which has included materials engineering (e.g., development of design values) and supply chain engineering (e.g., production feasibility studies) among others ensuring the connectivity of engineering requirements and manufacturing requirements.

A generalized engineering approach should include but is not limited to the following:

1. Define/understand part requirements
    a. Does part design require unique capabilities of AM? … Do conventional design practices apply or is there a different set of design requirements being applied?
2. Select design concept (basic geometry and material)
    a. Define build direction based on part function, support strategy and material stock for removal
    b. Refine design through iteration as necessary
3. Prototype build(s) and perform failure mode analysis as required
4. Establish part specific design values based on the combination of material allowables, feature specific properties and properties of full-scale part, as applicable.
5. Predicted performance (e.g., static properties and predicted life) with scale factors
6. Fixed digital model for "as-printed" part (as discussed in Section 7.2.1.4)

Finite Element Analysis (FEA) and/or testing is typically used to determine worst case stress conditions. Factors that the FEA or material allowables do not capture such as surface finish, material factors (e.g. environmental degradation, grain growth, temperature) must be accounted for in the design values. Once the part worst case stress is established, it SHALL be shown that sufficient design margin exists to the appropriate material property design value. Design qualification is complete when all requirements have been shown to meet the associated design value. Figure 9: Design Margin to Design Value Illustration illustrates this approach for static properties.

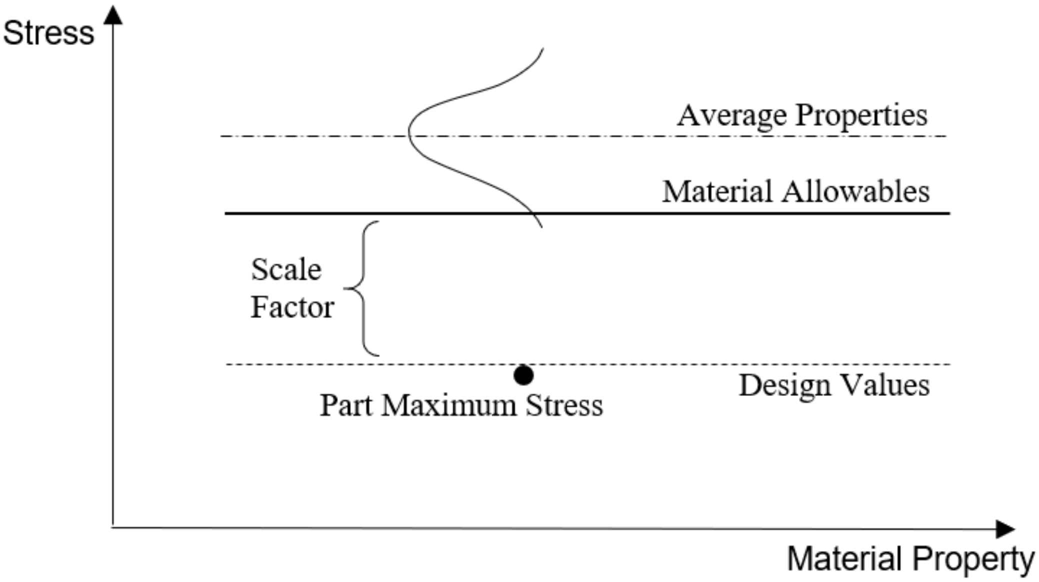

*Figure 9: Design Margin to Design Value Illustration*

## 11 System Qualification

System qualification is defined as the demonstration that a specific part design meets its intended function with safe operation over its design life. System qualification requirements are defined by the intended application and desired functionality.

For a new design, as with all parts regardless of method of manufacture, the AM part SHALL always be considered within the context of its larger system such that any system-level interactions will be included. Adequate system level performance SHALL be demonstrated to confirm the suitability and durability of materials to meet the application's performance level requirements. This is typically established by experience, analysis, and/or testing. This system level consideration should incorporate assembly component interactions – direct and indirect - and possible cascading failure events. Pathways for structural loading, non-structural loading, electrical grounding, electromagnetic interference grounding, dimensional fit including sealing surfaces, wear, vibration harmonics, secondary cooling flow, and other functional interactions between components of an assembly should be considered and tested to assure additively manufactured parts function as expected within the overall system.

Implementing AM for an existing design previously produced using traditional fabrication methods dictates the need for some if not all of the system qualification to be repeated. The function of the additively manufactured part and the overall design of the system SHALL be considered. The design approval holder determines how much of the original qualification SHALL be repeated based on certification, part requirements, and system criticality.

Part criticality is independent of manufacturing process. This is also the case for system-level criticality. Regardless of the fabrication method for parts in the assembly and system, determination of the criticality level is determined by the system's function. Application of AM to manufacture parts SHALL be designed and qualified in a manner consistent with the system criticality category independent of manufacturing processes used for any of the individual parts within the assembly or system. This is no difference in system level requirements for systems containing AM components or those containing exclusively traditional fabricated components.

The continued airworthiness plan needs to be considered at the system level including possible failure modes unique to AM.

# QUALITY CONTROLS

The quality control approach is based upon the completed PQ and finalized build configuration, including all parts, supports, and separately built coupons. This includes aspects of part quality which vary with the process that have been verified through the successful completion of OQ and PQ.

## 12 Production Process Quality Controls

This section considers the production process quality controls needed, which are separate from production part quality plan. Production process quality control are those process monitoring metrics (e.g., material inspection, surface finish, dimensional) implemented to ensure PQ is maintained (see section 7.3). It is typical that production process quality controls are monitored using Statistical Process Control (SPC) methods. Once PQ is established, a quality plan may be implemented.

### 12.1 Process Failure Modes & Effects Analysis

A Process Failure Modes & Effects Analysis (PFMEA) lists all the steps required to produce a part and determines the risks and potential modes of failure and consequences for each step. A complete PFMEA addresses human factors (i.e., operator performance), materials, machines, measurement systems, and environmental factors. After completing the PFMEA, production process controls SHALL be established which incorporates monitoring metrics to mitigate risks identified by the PFMEA.

## 13 Build Quality Plan

The quality plan for a production build is a means by which every part is shown to meet specification requirements. This should be developed in a cross-functional Failure Modes & Effects Analysis (FMEA) approach including design, materials and supply chain. The quality plan includes the build requirements:

- Orientation
- Part(s) location on platform or build area
- Type of test bar/ specimens on platform or build area
- Geometry of each test bar/ specimen
- Location of each test bar/ specimen
- Dimensional inspection plan
- Functional test plan

The quality plan also includes destructive and non-destructive evaluation:

- Part cut-up plan and sampling rate
- SPC of key process characteristics (e.g., tensile properties, grain size, chemical composition, density)
- Non-Destructive Inspection (NDI)

Build sampling may be established based on the part producer approved quality system.

### 13.1 Statistical Process Control

Part production builds should have defined SPC/sampling plans and control charts for part acceptance and trend analysis. As an example, control charts for KPV, mechanical properties, and surface roughness may follow ASTM E2587, Standard Practice for Use of Control Charts in Statistical Process Control and maintained within the process quality control program. Execution of the SPC would be contingent on the production machine maintaining active qualification status per this section.

### 13.2 Non-Conformance

Builds with results violating drawing or specification limits SHALL be assigned a non-conformance and may require an evaluation of the part and process history. Corrective actions should be taken for any non-conformance that cannot be uniquely isolated to the non-conforming build, and likely due to systematic faults, to prevent additional non-conformances. The machine may also be given an inactive qualification status until the conclusion of the evaluation, and all necessary corrective actions are complete. Documentation closing the non-conformance may recommend either returning the machine to active qualification or re-qualifying the machine based on the nature of the non-conformance and necessary corrective actions.

### 13.3 In-Process Repair:

Any rework required for a component by the part producer (including un-planned build interruptions) SHALL be first approved by the MRB.

## 14 Inspection

The discussion of inspection in this context refers to supply chain inspection and does not cover topics related to the inspection of post-run fielded parts. Inspection techniques to reliably detect and categorize anomalies are required as part of the production process. These techniques can include visual, geometric feature verification, leak testing, liquid penetrant, eddy current, ultrasonic, radiographic, infrared imaging, and/or computed tomography. The chosen technique(s) should be capable of reliably detecting critical flaws and/or anomalies within an AM part and comparing that information to the quality requirement. Inspection occurs within one of three categories:

- Material inspection
- Dimensional inspection
- Functional performance inspection

### 14.1 Material Inspection and NDI

Nondestructive inspection (NDI) requires unique techniques when used for component manufacturing. Anomaly types, sizes, morphologies, and distributions may be highly dependent on the manufacturing process, even for the same alloy. Hence the anomaly morphology may vary significantly in parts fabricated from a given alloy via AM, castings, or forgings. Typical inspection methods (x-ray, fluorescent penetrant inspection (FPI), computed tomography (CT), etc.) are appropriate for materials of all manufacturing methods, including AM products. In each case, unique parameters should be developed to detect the anomalies produced within each process. The type and size of anomaly to be detected will establish the required NDI technique(s). Acceptance criteria is dependent on the part criticality and application (e.g., static vs. fatigue properties) and will be documented within the quality requirements. Seeded defect studies and fractography are often the methods by which the NDI technique is qualified.

### 14.2 Anomalies and Defects

Additively manufactured parts may possess certain internal or surface features that are anomalous to the bulk structure. These features are a by-product of the manufacturing processes. The part requirements SHALL define acceptable limits for each of these anomalies and translated into quality requirements. Only when these thresholds are exceeded is the anomaly then characterized as a defect and SHALL be submitted to MRB.

Below are some common examples of additive material anomalies:

- Porosity is the entrapment of small gas bubbles common to metal solidification processes.
- Inclusion is a small particle which is chemically different than that which is allowed by the specification.
- Surface indication with a linear morphology.
- Lack of fusion is a condition where the melting is incomplete, leading to lack of homogeneity in the resulting material. Lack of fusion can happen in both powder and wire deposition processes.
- Surface condition refers to the surface morphology and roughness.

### 14.3 Dimensional inspection

Qualification to dimensional requirements is closing the loop from product requirements to the full supply chain. Each applicant SHALL ensure that every part from every machine will meet its design intent. In general, this is a 100% dimensional part verification. Any performance requirement such a as fluid flow should also be measured. This is typical of qualification from any conventional manufacturing method. Items that may be specific to additive manufacturing are the increase of part complexity (often requiring more advanced inspection methods or more cut-ups to access internal features) and the fact that process stability is dependent on parameters unique to the additive process itself.

Physical inspection includes all quality processes involving a physical measurement of the component. Though not unique to additive manufacturing, an appropriate physical inspection plan SHALL be established. Demonstration of physical measurement control may include physical inspection methods such as:

- Micrometer inspection
- Coordinate measurement machine (CMM)
- Structured light
- External surface laser scanning (to confirm geometric/dimensional conformity)
- CT scanning
- Part cut-up & sampling
- Flow testing
- Functional tests
- Proof test
- Surface roughness measurement

### 14.4 In-Process Monitoring for Inspection

When in-process monitoring systems are used as means of inspection; these systems SHALL be properly validated. Typically, in-process validation is performed by comparison to traditional inspection measurements

# CONCLUSION

Additive manufacturing is quickly growing for production use in aerospace because of weight savings, design freedom, flow time reduction, and cost savings.  Today's state-of-the-art equipment is increasingly utilized for fabricating components in prototyping while production clearance still presents a significant challenge in assuring part-to-part repeatability.  This report outlines the current industry best practices in the areas of material/process development, part/system qualification, and development of material allowables and design values, based on collective experience. In summary, qualification can be achieved using established and proven methodologies as a baseline, supplemented with additional focus on issues unique to AM.

# APENDIXES

## 15 Appendix A - Definitions and Terms

### 15.1 Definitions

**Design Value:** Material properties that are established from test data on a statistical basis and represent the finished part properties. These values are typically based on material allowables and adjusted, using building block tests as necessary, to account for the range of part specific features and actual conditions. Design values are used in analysis to compute structural design margin (e.g., margin of safety).

**Key Process Variable (KPV):** Elements of the AM process (e.g., build plate configuration, build layout, energy level, layer thickness, inter-pass temperature, melt pool environment, etc.) that, if changed, could affect physical, mechanical, metallurgical, dimensional, chemical, or performance characteristics.

**Material Allowable:** Material values that are determined from test data of the bulk material on a statistical basis. Allowable development approaches are established via industry standards such as MMPDS or company specific methodology and are based on testing conducted using accepted industry or company standards.

**Material Review Board:** A cross-functional group that reviews non-conformances on production parts and determines their disposition, which may include scrap, rework, or return to part producer.

**Part Producer:** Producer of additive manufactured parts including sources internal or external to the DAH.

**Powder Blending:** Powder blending is performed to achieving a homogenous end state from two separate quantities of powder.

**SHALL** – The word "SHALL" is used in this document (and capitalized to emphasize its intentionality) when a recommended requirement is being suggested for inclusion within future industry consensus standards, regulatory policy or guidance.

**Should** – The word "should" is used for recommended means of compliance. There may be known exceptions to these practices.

**Supply Chain:** in the context of this document, includes raw material, part and service providers both internal and external to the DAH.

### 15.2 Acronyms used in the report

AIA – Aerospace Industries Association

AM – Additive Manufacturing

AMS – Aerospace Material Specification

ASTM – ASTM International (formerly, American Society for Testing and Materials)

AWS – American Welding Society

CAD – Computer Aided Design

CFR – Code of Federal Regulations

CMM – coordinate measurement machine

CT – computed tomography

DaDT – durability and damage tolerance

DAH – Design Approval Holder

DED – directed energy deposition

DOE – Design of Experiments

EB-PBF – Electron Beam Powder Bed Fusion

ECM – Electro-Chemical Machining

EDM – Electro-Discharge Machining

EMI – Electro-Magnetic Interference

FAA – Federal Aviation Administration

FAT – Factory Acceptance Test

FMEA – Failure Modes & Effects Analysis

FPI – Fluorescent Penetrant Inspection

HCF – High Cycle Fatigue

HIP – Hot Isostatic Press

IHS – Industrial Health and Safety

ISO – International Organization for Standardization

KPV – Key Process Variable

LCF – Low Cycle Fatigue

L-PBF – Laser Powder Bed Fusion

MMPDS – Metallic Materials Properties Development and Standardization

MRB – Material Review Board

MRO – Maintenance, Repair, and Overhaul

MSFC – Marshall Space Flight Center

NASA – National Aeronautics and Space Administration

NDI – Non-Destructive Inspection

OEM – Original Equipment Manufacturer

PBF – Powder Bed Fusion

PCD – Process Control Document

PFMEA – Process Failure Modes & Effects Analysis

PPE – Personnel Protective Equipment

PSD – Particle Size Distribution

SAE – SAE International (formerly, Society of Automotive Engineers)

SPC – Statistical Process Control

STL – Standard Tessellation Language

WG – Working Group

## 16 Appendix B - Contributing Individuals and Organizations

| **Organization** | **Representative** |
|---|---|
| Airbus | Stephane Bianco |
| Airbus | Alain Santgerma |
| Boeing | Eric Sager |
| Boeing | David Polland (WG Vice-Chairman) |
| Boeing | John Stoll |
| Bombardier | Leo Kok |
| Collins Aerospace | Sue Margheim |
| Delta Air Lines | Ramesh Ramakrishnan |
| Federal Aviation Administration (FAA) | Robert Grant |
| Federal Aviation Administration (FAA) | Michael Gorelik |
| General Aviation Manufacturers Association (GAMA) | Joseph Sambiase |
| GE Aviation | Mark Shaw |
| GE Aviation | Jeff Conner |
| HEICO | Jeff Paust |
| Honeywell | Brian Hann (WG Chairman) |
| Lockheed Martin Sikorsky | Ryan Patry |
| Parker Aerospace | Robert Pelletier |
| Rolls-Royce | Amit Chatterjee |
| SAFRAN | Yann Danis |
| SAFRAN | Jean-Francois Fromentin |
| Spirit AeroSystems | Paul Toivonen |
| Textron Aviation | Amit Tamhane |
| Textron Aviation | Bret Vogel |