AIA AEROSPACE INDUSTRIES ASSOCIATION

Recommended Guidance for Certification of AM Components

October 2025

AIA Additive Manufacturing Working Group

Preface

This latest revision of the *Recommended Guidance for Certification of AM Components* builds on the initial release reflecting changes, advancements, new releases, and the growing maturity of the additive manufacturing (AM) industry. These updates address the increasing use of AM in aerospace, ensuring that the certification of parts—particularly more critical components—meets regulatory and safety requirements.

This revision offers additional methodologies for design data development, especially for high-criticality components. The focus on durability and damage tolerance data set development introduces additional approaches to establishing material allowables and design values. By ensuring the collection of fatigue crack growth and fracture toughness data, these updates provide a stronger foundation for the long-term reliability of AM parts. For critical parts, understanding the effects of Key Process Variables (KPVs) and controlling microstructure and defect morphology are vital to maintaining structural integrity under operational conditions.

Beyond material qualification, the revision also expands non-destructive inspection (NDI) methods, offering guidance on adapting existing inspection techniques to AM-specific requirements. This is especially relevant for complex, high-criticality components where traditional inspection methods may be insufficient. The report introduces advanced NDI techniques for detecting internal defects in intricate geometries, providing more effective ways to ensure the integrity of critical parts before they are deployed.

Another enhancement in the latest revision is the focus on Process Control Specimens (PCS), or witness coupons, which are essential for verifying process stability and repeatability. For high-criticality components, PCS are integrated into the production workflow to ensure consistency across production runs and that material properties meet the required safety margins. By validating KPVs through PCS, producers can maintain tight control over the process, ensuring that even slight deviations are detected and corrected before critical parts are produced.

The report also aligns with updated FAA regulations such as 14 CFR 2x.603, 2x.605, and 23.2260, and incorporates ASTM F3572-22 standards. This introduces a criticality-based classification framework that ensures high-criticality components meet stringent certification standards. This revision provides comprehensive guidance for assessing the safety, performance, and compliance of AM parts based on their failure consequences, offering greater clarity and structure for certifying critical components.

The *Recommended Guidance for Certification of AM Components* is an essential resource for aerospace engineers, certification professionals, and regulatory bodies. It equips stakeholders with the tools to navigate the path of certifying AM parts, particularly for high-criticality components where safety and reliability are paramount. By integrating the latest advancements in AM technology and regulatory requirements, this report ensures that organizations can meet increasingly rigorous standards while leveraging the benefits of additive manufacturing.

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 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 Additive Manufacturing Working Group was formed in 2015 by AIA with the objective to support development of effective and consistent guidance for design, manufacture, and certification of aviation parts produced via AM processes and produced an initial report in 2020. This major revision restructures portions of the document, reflects maturation of the additive manufacturing (AM) industry, and introduces recommended practices for the certification of AM components in applications of higher criticality. Nonetheless, this report remains applicable to all criticality classes. Additionally, the AIA working group has released a white paper offering guidance on working with AM components in Maintenance, Repair, and Overhaul (MRO). This paper also provides guidance for compliance to 14 CFR 2x.603, 2x.605, 2x.613, 23.2260, 33.15, 35.17, and 14 CFR 21.137 for metal powder bed fusion (PBF) and directed energy deposition (DED) additive processes. Classification of a part's criticality is the outcome of failure modes, effects, and criticality analysis (FMECA), addressing modes such as fatigue, crack growth, and residual strength. Within this paper, higher-criticality parts are those which have a higher consequence of failure. Additional guidance is provided for parts with more complex failure modes and a severe consequence of failure (higher criticality) subject to FAA rules 14 CFR 23.2240, 2x.571, 33.14, 33.70, and 35.37. A standard practice for four levels of classification has been defined by ASTM F3572-22[1], ranging from high to no consequence of failure, however these levels of classification are not explicitly used in this document. This report delves into considerations and current industry best practices in the areas of material/process development, part/system qualification, and design data development. The authors are aerospace industry design approval holders, users of the equipment, and additive manufactured part end users, and hence provide an experienced and qualified perspective on these issues. In summary, AM development, qualification, and certification 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, methods of compliance to applicable regulations.

[1] ASTM F3572-22 Standard Practice for Additive Manufacturing – General Principles – Part Classifications for Additive Manufactured Parts Used in Aviation

4 Contents

5 Background

Additive manufacturing has great potential in the aerospace industry as a transformative 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. Current powder bed fusion and directed energy deposition machines are highly capable for prototyping. However, there is a need to establish controlled and repeatable materials and processes when the goal is to achieve safe performing products that meet design requirements, demonstrating effective part certification. Whether by public domain standards or proprietary standards, these controls are reliant on end-user protocols that ensure part-to-part repeatability with sound inspection technologies to validate required performance, in terms of material properties and part function. While currently used aerospace component 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) and Production Approval Holders (PAH) should undertake when seeking regulatory approval of AM components. This report can also benefit AM suppliers that are seeking more understanding of the certification process and responsibility. Specifically, it focuses on metal AM components fabricated using powder bed fusion (e.g., laser and electron beam) and directed energy deposition (e.g., wire and powder; laser, plasma arc, electron beam, etc.) and has general applicability to other additive processes. 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. Additional guidance is provided for parts with more complex failure modes and severe consequence of failure (higher criticality) subject to the FAA rules 14 CFR 23.2240, 2x.571, 2x.602, 33.14, 33.70, and 35.37. Classification of a part's criticality is the outcome of a failure modes and effects criticality analysis (FMECA), addressing modes such as fatigue, crack growth, and residual strength. An additional resource for determining levels of classification of AM components is presented in ASTM F3572-22, ranging from high criticality to no consequence of failure. Within this paper, higher criticality parts are those that have higher consequence of failure and may introduce the need to address more complex failure modes. For further information on failure modes associated with AM, see **Section 8.1.**

Although not comprehensive, this report addresses the subjects below pertinent to AM qualification.

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

Complete life cycle considerations of the technology, such as scrap handling and disposal, are beyond the scope of this document. The reader should exercise due diligence when implementing best practices for materials and processes beyond the scope of this document. Definitions of commonly used terms are provided in Appendix A – Definitions and Terms

5.2 AM Component Qualification and Certification Process Overview

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 understands Key Process Variables (KPVs) and their impact on the final product. A complete showing of the certification pathway discussed in Section 5.3 SHALL be addressed at the time of certification.

Some have referred to additive manufacturing 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, performance qualification, and design verification 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, which includes activities such as parameter development, initial material testing, material specifications development, post-process development, part process development, machine operational qualification plan and machine monitoring plan (e.g. machine configuration, preventative maintenance and calibration). A final objective is the machine operational qualification in accordance with the Process Control Documents (PCD) and the material specification.

Supply Chain Qualification– Supply chain qualification is demonstration and approval of the suppliers to manufacture feedstock or part to the type design intent. 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. To utilize additively produced alloys, material property data is developed to substantiate the performance of the alloy as dictated by the DAH and regulatory requirements.

Part Design Certification Processes –Although PBF & DED are relatively new processes for aerospace, the established verification processes and standards still apply to the final product. Due to the increased consequence of failure of higher criticality parts, care should be taken to understand and account for the variation in material and perfomance that can be present in additively manufactured parts see Section 8.1. A building block approach is recommended to address items such as scale factors, environmental factors (e.g. operational conditions), 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 emphasis on microstructural features, 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 material, process, and inspection specifications 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 areas is what is most relevant. (Note: Not included here are details surrounding repair and maintenance of AM parts after operational service.) See "Industry Guidance and Best Practices for AM Repair and Alteration within the MRO Environment" for this additional scope.

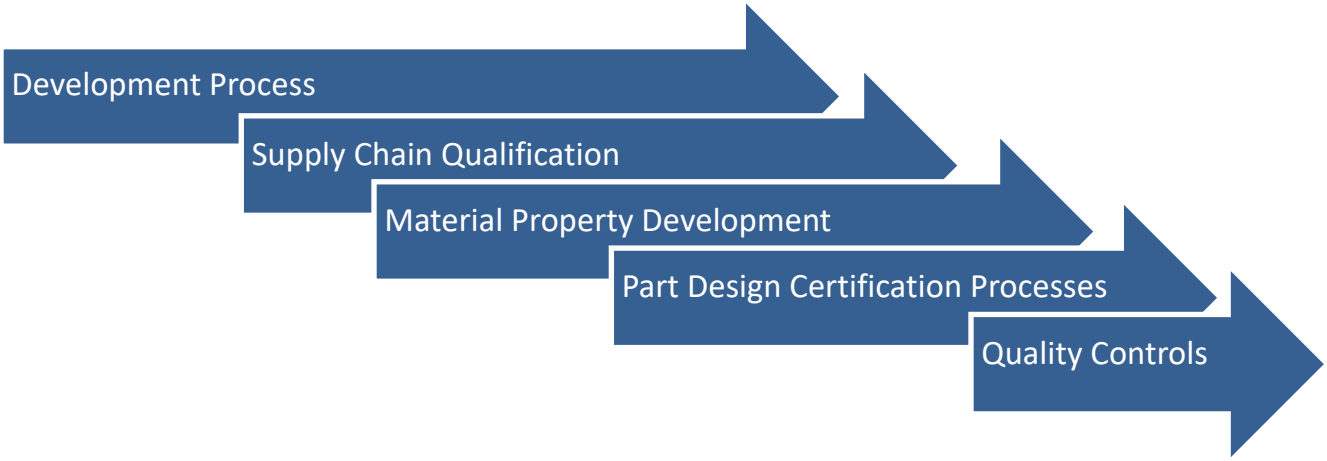

Figure 1: Additive Development, Qualification, and Certification Areas

While there is a dedicated Material Property Development step, material data is generated 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.), specimens excised directly from additively manufactured parts if it is possible, and / or correlate with the material characterization. Material data generation at different stages of the additive manufacturing development and qualification process is shown in Figure 2: Material Data Generation at Different Stages of the Additive Manufacturing Development and Qualification Process below, with additional details provided in the sections referenced in the figure. Installation Qualification (IQ), Operational Qualification (OQ), Material Qualification (MQ) and Performance Qualification (PQ) are shown in the overall development and qualification process.

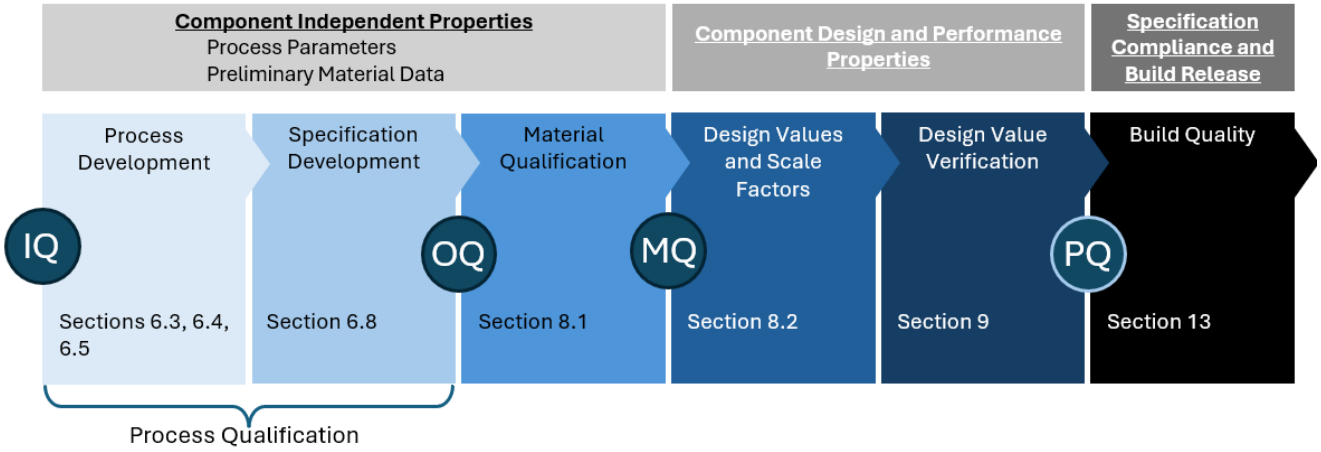

Figure 2: Material Data Generation at Different Stages of the Additive Manufacturing Development and Qualification Process

5.3 Certification Pathway

Ensuring the structural integrity of a product is a paramount concern in aviation engineering. To achieve this, a systematic approach to testing is recommended, culminating in the type certification of product designs in compliance with regulatory requirements. Additive Manufacturing does not require deviation from current regulatory frameworks; the following certification pathway does not differ from other material and process combinations. The certification plan structure, organization, and constituent elements, including analysis supported by test evidence, serve as a foundational framework for this process, encompassing various levels of testing, with intermediate maturity elements between levels, from material characterization to full air vehicle validation. Figure 3 provides a systematic framework with each level of the test pyramid diagram highlighting a focal significance culminating in an ability to validate and certify product designs. This comprehensive approach involving robust testing ensures the safety, reliability, and regulatory compliance of aerospace systems, instilling confidence in their performance and suitability for commercial deployment of additive manufacturing technology. The use of experimental design tools, numerical simulation methodologies, and statistical analysis used to refine test data and quantify uncertainty during the development process are beyond the scope of this document. As levels of the pyramid are developed, the test data allows for additional analysis validation and reduces future test burden for subsequent designs.

Below is a delineation of the differentiating objectives and contributions for each layer. By addressing applicable levels of testing, from microstructure characterization to full air vehicle level validation, engineers establish the reliability, robustness, and compliance of product designs.

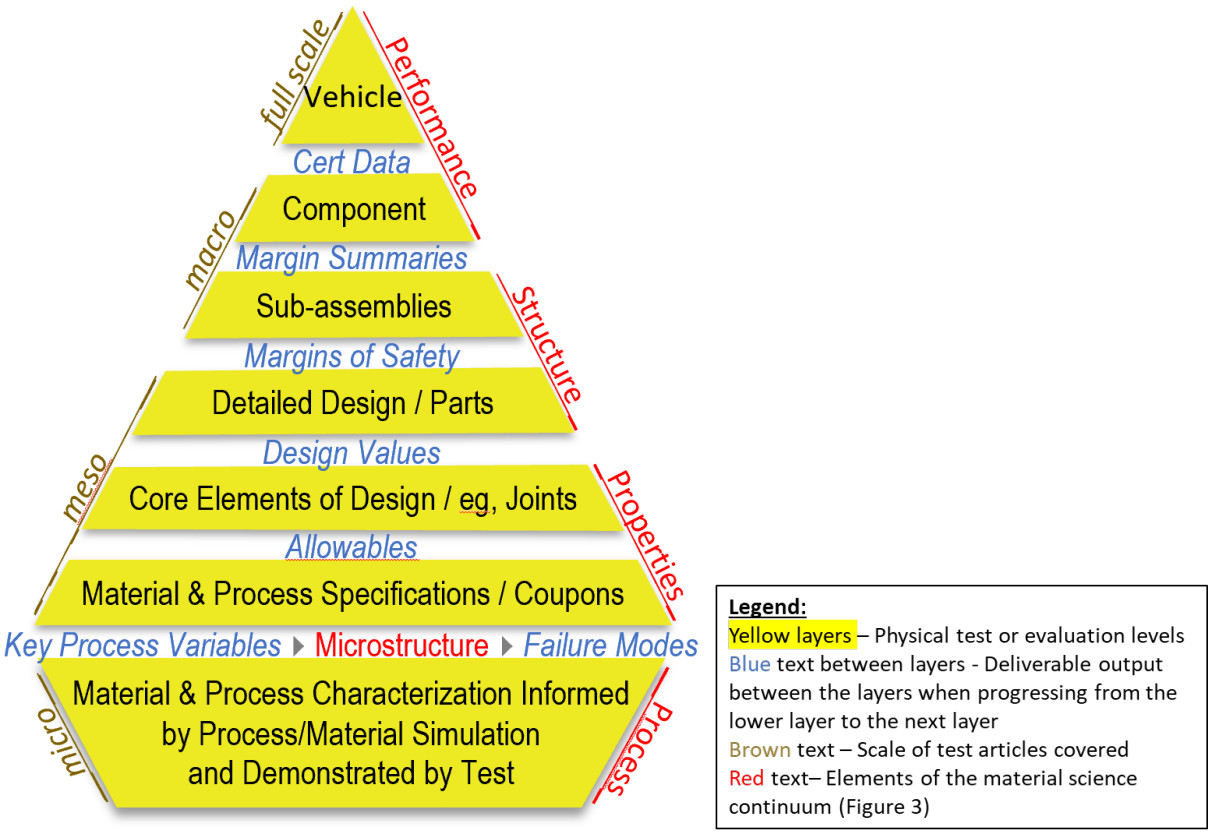

Figure 3 Development and Verification Steps, a Certification Pathway

Material and Process Characterization:
At the base of the test pyramid lies microstructure characterization, where engineers analyze the internal structure of materials at a microscopic level. This involves examining grain boundaries, phases, and defects to ascertain key process variables that enable baseline property objectives and failure mode behaviors. Characterization and maturation of a potential material and process is iterative in the development of the material and process specifications to achieve target performance levels. Microstructure characterization serves several critical purposes:

Characterization of Baseline Performance: By association of microstructural features with mechanical testing, engineers establish baseline processing window and its impact on material performance. This foundational data informs subsequent testing and analysis.

- **Identifying Anomalies and Defects**: Detecting anomalies or defects in the microstructure early on allows engineers to address potential weak points in the material as they contribute to failure modes. This proactive approach enhances the safety and reliability of the product.
- **Ensuring Consistency and Reproducibility**: Statistical analysis of microstructural features enables engineers to assess the consistency and reproducibility of material properties across batches or production runs under validation of key process variables. This ensures that the material meets specified requirements with a high degree of certainty.

Material and Process Specification and Coupon Level Testing

Characterization leads to a defined set of requirements and limits documented in material and process specifications and process control documents (PCD). After a stable and repeatable process is established, bulk material properties can be developed. A key goal in this step is to ascertain and characterize the inherent variability introduced by the feedstock and AM processes.

- **Quantifying Material Properties (Allowables and Design Data Sets)**: Testing coupons, see **Section 8.1**, allows engineers to quantitatively measure material properties such as tensile strength, yield strength, fatigue, and fracture toughness. Analysis of these properties provides insights into material behavior under different loading conditions.
- **Process Robustness**: Through rigorous testing and statistical analysis, engineers demonstrate the robustness of the manufacturing process. This instills confidence that the process will be controllable, including control sensitivity, and repeatable within a defined process window.

Core Elements of Design:

In addition to bulk material properties, engineers need to also characterize detailed design features. Using AM may result in unique artifacts (e.g. geometric, performance gradients, anomaly distribution and multiple variant failure modes) for which there is limited or no prior experience. This will require additional characterization, which can cause challenges in design value development, manufacturing, inspection, and certification. This level of testing involves analyzing coupons representing specific joints, features, or design elements used in product construction. Material and design detail characterization serve the following key objectives:

- **Design Values:** Testing core elements of design, see Section 8.2 allows engineers to characterize the features that impact failure mechanisms at the detail design level.
- **Feature Reliability and Robustness**: Through rigorous testing and analysis, engineers demonstrate the reliability and robustness of the design and effects of manufacturing process on design characteristics. This instills confidence that the feature will perform as intended under operational conditions. Note that some reliability metrics may be driven by economic considerations.

Detail Design and Parts

At this level, engineers incorporate form, fit, and function into the part definition to achieve application requirements. This involves combining methods of analysis with design values to establish margins of safety at the part level for each feature, using engineering judgment backed by appropriate due diligence to choose the critical features for analysis.

- **Validating Design Assumptions**: By subjecting parts to structural testing, engineers validate design assumptions and ensure that critical features meet performance requirements. Analysis of test results helps verify the adequacy of design.
- **Validation of Methods**: Ensure methods of analysis are valid across meso scale and determine margin of safety as an output.

Note: The following sections are largely undifferentiated from standard practices. Best practice suggests testing up to the next level of the pyramid to demonstrate full confidence of the design to ensure reliability of the additive manufacturing component and demonstrate compliance to requirements when installed on the air vehicle.

Sub-Assembly Testing
Moving up the test pyramid, engineers transition to single part and sub-assembly testing. This intermediate level of testing involves validating the structural integrity of individual components and assemblies. Single part and sub-assembly testing serve the following purposes:

- **Building upon Characterization Data**: Leveraging the data obtained from microstructure characterization and material/design detail characterization, engineers validate the structural integrity of individual components and assemblies. This data serves as a reference point for assessing the performance of larger-scale structures within the airframe.
- **Integration and Interaction Assessment**: Sub-assembly testing involves assembling multiple components into cohesive units, such as wing sections or fuselage segments. By subjecting these assemblies to structural testing, engineers evaluate the integration and interaction of components, ensuring compatibility and performance consistency. Testing at this sub-assembly level allows the introduction of complex loading conditions that are not practical to be accomplished at lower levels. This step of integration also allows the early assessment of failure modes and durability performance.
- **Incremental Validation**: Single part and sub-assembly testing represent incremental steps towards full air vehicle validation. By progressively testing smaller subsets of the airframe, engineers can identify and address issues early in the design process, minimizing risks and optimizing performance before moving to larger-scale testing.

Component Testing:
As engineers advance to component testing, they scale up the complexity of testing to include complete structural elements such as wings, fuselages, and empennages. Component testing builds upon the insights gained from single part and sub-assembly testing and serves the following objectives:

- **Scaling Up Complexity**: Component testing represents a scaling-up of complexity from single part and sub-assembly testing. By integrating multiple sub-assemblies into complete structural components, engineers simulate real-world operating conditions and assess the performance of critical airframe elements under load.
- **Validating System-level Behavior**: Component testing provides a platform for validating system-level behavior and interactions within the airframe. By testing complete structural components, engineers gain insights into how different systems, such as aerodynamics, structures, and propulsion, interact and influence overall performance.
- **Refinement of Design Assumptions**: Component testing allows engineers to refine design assumptions and optimize structural configurations based on empirical data. By correlating test results with analytical models and simulation predictions, engineers can iteratively improve the design to meet performance objectives and regulatory requirements.

Full Air Vehicle Level Validation Testing:
At the apex of the test pyramid is full air vehicle level validation testing, where engineers integrate all components and systems into the complete aircraft configuration. This final stage of testing builds upon the foundation established through microstructure characterization, material and design detail characterization, single part and sub-assembly testing, and component testing. Full air vehicle level validation testing serves the following critical functions:

- **Synthesis of Testing Insights**: Full air vehicle level validation testing synthesizes insights gained from all preceding levels of testing, providing a comprehensive assessment of the airframe's structural integrity, performance, and compliance with regulatory requirements.
- **Real-World Simulation**: By subjecting the complete aircraft to a battery of tests, including static load testing and flight test validation, engineers simulate real-world operating conditions and evaluate the aircraft's behavior under various flight scenarios.
- **Demonstration of Compliance**: Full air vehicle level validation testing serves as the ultimate demonstration of compliance with regulatory standards and certification criteria. By successfully completing validation tests, engineers provide regulators with the assurance that the airframe meets all safety and performance requirements, paving the way for certification and commercial deployment.

DEVELOPMENT 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 metallurgy 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 4 is a simple schematic of the well-known material science continuum.

Figure 4: Materials Science Continuum

Material and process development should consider the criticality of the targeted part application(s). The process development is described in more detail in the following sections with the objective of maintaining the specified microstructure in the as built material and achieve the desired modified microstructure and material properties in the subsequent post processes. Material performance is determined once the process is fixed and qualified.

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). Feedstock suppliers may work to internal specifications, within the bounds of the feedstock specification; it is the design applicant's responsibility to understand the implications of differences between these specifications. Feedstock that does not comply with the material specification SHALL be rejected or dispositioned through the Material Review Board (MRB) process.

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

- Chemical composition
- Impurity limits
- Atomization media/method
- Cleanliness and contamination limits
- Particle size distribution and morphology

- Acceptance of 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:

- Chemical composition
- Impurity limits
- Melting practice
- Surface condition, including surface quality and cleanliness
- Size and tolerance
- Twist and coil
- Straightness
- 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.

- AMS7001 “Ni Base 625 Super Alloy Powder for Use in Laser Powder Bed Additive Manufacturing Machines”
- AMS7002 “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. AMS4954)
- American Welding Society specifications (e.g. AWS A5.16)

If no standard feedstock specification is available or appropriate, the design applicant SHALL develop such a specification.

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 within the chosen AM modality. 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 design applicant 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 AM machine OEM 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 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 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 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 anomalies such as lack of fusion and porosity. Figure 5 illustrates the results of such a DoE.

[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).

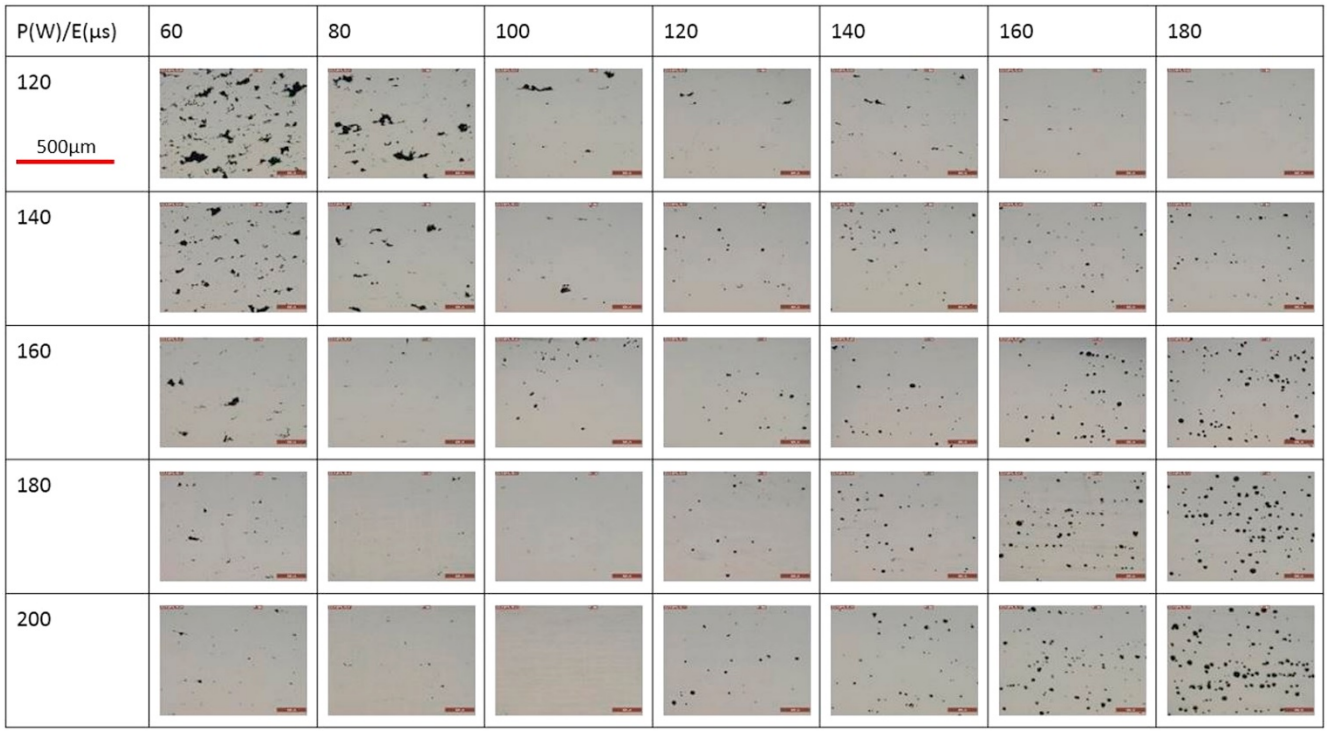

Figure 5: Global Energy Density Versus Lack-of-Fusion (LOF) & Porosity for L-PBF[3]

Even if a design applicant receives or purchases optimized parameter sets from an AM machine OEM 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, minimizing build times may adversely impact material density, residual stress, thermal gradients, distortion, and microstructure, etc. and hence a series of DOEs may be executed to optimize part density and build speed.

6.5 Inspection Process Development

As part of the development of a robust parameter set for the build of parts, an inspection process must be aligned to ensure consistency in the manufacturing process and forms the basis of inspection. Anomalies inherent in the process, which, when maintained within limits, are generally acceptable and characterized as a part of the material specification. Anomalies inherent to the manufacturing process should be characterized and understood. Various standardized inspection methods are available to detect anomalies at the surface, near-surface, and internal volume of the part. Destructive methods such as metallography can be used to characterize the material anomalies inherent to the manufacturing process. This data may be used to assess the capability limits of the developed inspection process. Desired outcomes are to determine the limits of detection using economical NDI methods and probability of detection (POD) of anomalies of various sizes. NDI methods need to be performed at relevant stage(s) throughout the end-to-end manufacturing process because anomalies may vary in

3 Haider Ali, Le Ma, Hassan Ghadbeigi, Kamran Mumtaz, In-situ residual stress reduction, martensitic decomposition and mechanical properties enhancement through high temperature powder bed pre-heating of Selective Laser Melted Ti6Al4V, Materials Science and Engineering: A, Volume 695, 2017, Pages 211-220, ISSN 0921-5093,

morphology and detectability during manufacturing processing. This data is used in the material inspection criteria and in later design value development. Certain AM attributes may require functional performance verification testing and these effects should be understood early in the development cycle, such as potential for leak paths through thin wall structure or flow restrictions.

Future in-process monitoring inspection techniques may be able to justify reduction or replacement of traditional inspection methods. Development of the inspection methods SHALL be evaluated throughout the material science continuum in parallel with the full development process. As per any manufacturing process, the maintenance of a stable control process is paramount to the production of quality parts. A quality plan to ensure adherence to the consolidated material specification and process specification as defined in Section 6.8 is to be developed. Monitoring and providing a disposition of the in-process parameters for inclusion in the PCD provides an opportunity for maintaining process assurance as per Section 7.2.3.5. Further development of a more active processing control technique could also be developed as per Section 14.3 to ensure continuous process assurance. The identification of acceptance criteria for anomalies and defects per Section 14.1 will enable a visual record of items that a printed part must be compared against.

6.6 Develop Post-processing

Most materials require some post-build processing to be useful. Processing may include powder removal, support removal, machining, surface enhancement, hot isostatic pressing and/or thermal treatment. Post-processing is a broad term used for any process which occurs after the additive "printing" process is complete. A risk analysis of the impact of the post processes on the properties of the part is recommended to define the validation test plan and the associated KPV.

6.6.1 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.

Note: Some powder removal processes may have an impact on the material of the part and decrease the material properties. For example, vibratory systems may create high cycle fatigue cracks from harmonic resonance frequencies within the part.

6.6.2 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.

6.6.3 Removal from the Build Plate and Support Removal

In L-PBF, typical build plate removal processes include Electro-Discharge Machining (EDM), water-jet cutting, or bandsaw 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, electrochemical machining (ECM), or waterjet) and chemical removal via dissolution. The impact of these processes on subsequent surface integrity SHALL be understood. For DED, the build plate may remain a part of the component.

6.6.4 Hot Isostatic Pressing (HIP)

HIP has been shown to be effective to minimize internal anomalies (including lack-of-fusion or spherical porosity) when the anomalies are not surface-connected. It may also serve to homogenize localized chemical segregation and microstructure. The AM process may result in insoluble gas trapped within voids that may impair the HIP process. 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. For fatigue critical parts, certain material and process combinations may strongly benefit from post process HIP due to reduction in quantity and size of non-surface connected porosity. It should be noted that HIP may not be fully effective in addressing all types of anomalies and may in fact change anomaly shape and concentration. Any remaining anomalies SHALL be evaluated see Section 8.1.

6.6.5 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.[4] Also, direct aging of powder bed fusion Inconel 718 has revealed formation of extensive Laves phases, known to be detrimental to the strength and fatigue properties of Inconel 718.[5]

6.6.6 Surface Enhancement

Powder bed technology can be challenged to achieve sufficient surface roughness values. 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, conventional machining, 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. Traditional surface measurement metrics such as Ra may not be sufficient for characterization of the additive surface, other applicable measurement metrics may be more inclusive of the varying surface texture. Wire-fed technologies yield near net shapes and surfaces that are typically machined. Care should be taken to prevent obscuring of anomalies (i.e.,

[4] "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

[5] "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.

smearing) when surface enhancements are used prior to surface inspection. Fatigue and fracture critical applications are extremely sensitive to surface conditions. Some surface enhancement processes may have an impact on the material of the part and decrease the material properties. For example, chemical polishing could cause intergranular attack or pitting on the surface if appropriate processing parameters are not chosen.

6.6.7 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 are also generally applicable to AM materials, however care must be exercised as to the application to surface condition.

Most conventional coating and surface processes may be applicable to AM parts. The final performance of the protection schemes should be assessed with regard to the AM specific surface roughness, morphologies, oxide layers and microstructure. It is noted that the AM printed material may be functionally different than conventional alloys and hence novel coatings/corrosion protection schemes may have to be developed.

6.7 Preliminary Property Determination

Preliminary mechanical property evaluation is likely to be performed during process development, which then serves as a foundation for subsequent extensive characterization (see Section 6.8). Preliminary mechanical property data can be used in establishment of material specification minimum properties. This is, at a minimum, room temperature static tensile properties (i.e., 0.2% yield strength, ultimate tensile strength, and elongation). Preliminary evaluation of the anisotropy of the material according to X, Y, Z machine axis is recommended. The test matrix required for this data set should be determined by the accepted industry or design applicant material development practice (e.g., number of samples, number of lots). Examples of accepted industry practices for material specification minimum data generation and statistical analysis are Volume II of The Metallic Materials Properties Development and Standardization (MMPDS) Handbook Chapter 9 S-Basis guidelines, or data generation may also reference SAE AMS AM Metals General Agreement Data Submission Guidelines [6]. Fatigue and fracture material development practices and lifing methods are largely held by the design applicant. Consistent with the principles of the materials science continuum (Figure 4), specification development may include quantifying proxies for controlling strength, such as grain size and anomalies.

Preliminary evaluation of the impact of the roughness aimed for the part is recommended for fatigue properties. Preliminary evaluation of fatigue and damage tolerance properties is recommended for fatigue critical components at this stage of development. This evaluation allows for tailoring of the process to reduce scatter and/ or improve capability or selecting alternative material and process combinations.

6.8 Release Consolidated Material and Fusion Process Specifications

Consolidated 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.

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

6.8.1 Consolidated Material Specification

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

- Feedstock material specification.
- Material fusion process specification.
- Composition, including trace elements – 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 (See Section 14.1.1)
- Mechanical properties – at a minimum, room temperature tensile properties.

Material specifications may have grades or classes with differing requirements. It is the applicant's responsibility to determine the appropriate grade or class for the component.

6.8.2 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.

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

The process specification SHALL sufficiently define the process requirements. An example of expectations for the contents of process specifications can be found in FAA Order 8110.4C. If the process specification does not sufficiently define the process requirements, the PCDs (Section 7.2) would be required to be included in type design data definitions. Final determination of whether to include the PCD in the type design data package is agreed upon between the design applicant and the regulator.

Industry standards organizations have been active in developing guidance specifications for fusion and deposition processes; a sample of these relevant to aerospace products are listed below. Note that these are not process specifications but stand as a framework.

- AMS7003, "Laser Powder Bed Fusion Process"
- AMS7005, "Wire Fed Plasma Arc Directed Energy Deposition Additive Manufacturing Process"
- AWS D20.1, "Standard for Fabrication of Metal Components using Additive Manufacturing"

6.9 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:

6.9.1 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.

6.9.2 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.

6.9.3 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, see Section 6.4.

6.10 Machine Qualification

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 required level of performance under defined process controls for PAH qualification approval. The machine qualification follows the well-known approach of Factory Acceptance Test (FAT), Installation Qualification (IQ), Operational Qualification (OQ), and Performance Qualification (PQ).[7]

While cleanliness of the equipment is important for all applications, critical parts can require additional cleanliness controls due to higher sensitivity from contamination sources. Caution should be taken during machine procurement and throughout fabrication, shipping, installation, and subsequent factory acceptance test of machines that will be qualified to build critical parts. Specifically, purchasers, informed by PAH requirements, may need to specify controls on AM machine OEMs to limit feedstock materials and/or sources (e.g. powders, wires) that are dissimilar from critical part applications to prevent contamination sources during factory calibration of machines, or alternatively may need to work with AM machine OEMs to develop, validate, and enforce stringent cleaning procedures.

6.10.1 Machine Factory Acceptance Test (FAT)

The FAT is performed at the AM machine OEM 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, informed by the PAH requirements. 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.

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6.10.2 Machine Installation Qualification (IQ)

The Installation Qualification (IQ) occurs upon delivery and installation of the equipment to the part producer's facility and includes machine set-up, initial calibration, and a site acceptance test (SAT). The SAT will be used by the part producer to validate that each machine is performing to a minimum standard to accept delivery of a new machine. The SAT build is an AM machine OEM standard build or jointly agreed to by both the AM machine OEM and the part producer. This often involves the need for repeated trials until SAT requirements are met. The results between the FAT and SAT for a given machine should be consistent. Any variations should be investigated and corrected. 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 AM machine OEM are suitably considered.

6.10.3 Machine Operational Qualification (OQ)

Machine OQ occurs when the machine, tied to a specific serial number, has been qualified to a given material and process specification. These process controls will become PCDs as part of the PQ.

To conduct a Machine Operational Qualification, the part producer SHALL run a series of metallurgical, mechanical, and physical property tests to ensure the machine is capable of producing material that meets the required specification. Depending on intended application(s) of the machine, this test series may include fatigue and fracture toughness to ensure the machine satisfies their target applications. Material DOE or other methods may be used to evaluate acceptable performance within the established tolerance range of KPVs or impactful interactions of KPVs. Standard OQ builds SHALL demonstrate material performance and may include artifacts[8] to validate other metallurgical, dimensional, and surface roughness characteristics.

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. [9] OQ has been completed when it has been demonstrated that the material specification requirements can be met by the machine; including, where required, a demonstration of statistical relevance over multiple builds. Completion of the OQ is analogous to traditional process qualification.

8 "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).
9 Machine Qualification for Fusion-Based Metal Additive Manufacturing, AMS7032, August 2022.

SUPPLY CHAIN QUALIFICATION

7 Supply Chain Qualification

Additive manufacturing part producers, whether internal or external, require qualification by the production applicant or PAH. The part producer may be provided part and complete process requirements by the PAH, or the part producer, with the concurrence of the PAH, may participate in the development of the process requirements to meet the part requirements. All part producer quality organizations are responsible to meet the qualification requirements.

See "Industry Guidance and Best Practices for AM Repair and Alteration within the MRO Environment" for this additional scope. 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 or accreditations include ISO 9001, AS 9100, and NADCAP.

7.1 Supply Chain Qualification Flowchart

Figure 6 illustrates the purchaser requirement flow-down to the part producer and subsequent supply chain process flow.

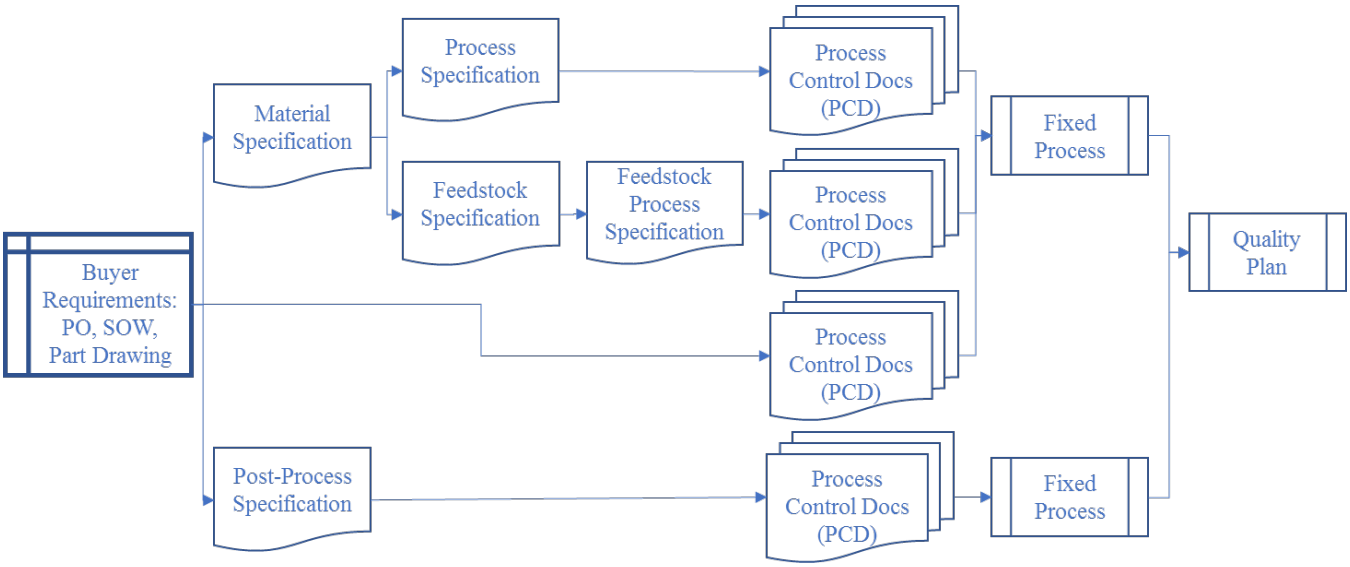

Figure 6: Supply Chain Qualification Flowchart

Supply chain qualification for AM largely follows traditional qualification with special attention to operator training and digital record keeping. Since AM is the manufacture of material, process, and part, the knowledge and competence of the supplier is essential to providing aerospace parts. It is recommended the PAH establish a supplier qualification plan for demonstration of a consistent level of competence.[10] The IQ/OQ/PQ process flow described in this paper is a proposed method of completing this demonstration. The level of expectation is higher, but requirements will likely evolve over time with experience creating a more dynamic relationship.

10 NASA-STD-6030 Additive Manufacturing Requirements for Spacecraft Systems, 2021-04-21 and NASA-STD-6033 Additive Manufacturing Requirements for Equipment and Facility Control, 2021-04-21

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. A Process Control Document (PCD) controls a specific process to ensure it stays within defined parameters of the process specifications and meets its quality requirements. The part producer PCDs SHALL be created, and a fixed process established. The PCDs SHALL be established by the part producer based on the requirements of the design applicant or DAH material specifications, process specifications, and the drawings. Once each process is qualified, the associated PCDs are fixed and any changes to the PCD SHALL require evaluation through a change management process and may include approval by either manufacturing, engineering or regulator prior to the change being implemented into production. DAH SHALL establish the approvals required for changes to the PCD. PCDs are typically defined for manufacturing processes which require process control to maintain stability to component requirements, or additional DAH requirements such as design values. Each unique build definition, included in the PCDs, needs to be qualified and controlled.

Though generally applicable, process control requirements for critical parts may be more stringent such as feedstock handling, cleanliness controls, gas purity etc. KPVs of critical parts should be tightly controlled because critical parts performance may be more sensitive to the impact of process drift and changes. A more extensive degree of justification and required level of approval, as prescribed by the DAH, may be required for changes to the PCD that affect the performance of a critical part.

Post-process operations that cannot be sufficiently controlled by part drawings and specifications should be controlled by a PCD. In this case, the PAH is responsible to provide all necessary part requirements for special processes to allow PCD establishment.

A non-exhaustive list of recommended Process Control Documents is provided for reference:

- 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
  - General Contamination Avoidance Plan
  - Machine and Material Alloy Change Contamination Avoidance Plan
- Part Production Plans
  - Engineering Requirements Flow Down 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 part 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 AM machine OEM 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 AMS7003 and MSFC-SPEC-3717.

As part of this training, the operator should be made aware of the potential consequences of deviations in the manufacturing steps, in particular when critical parts are produced. For example, FAA AC 27.602 / 29.602, the work instructions should clearly indicate the special nature of critical parts, in order to draw the attention of operators involved in producing these parts. Critical parts may require qualification of personnel with a higher level of experience. When operators are permitted to adjust machine critical process variables, additional classes of personnel qualification requirements should be considered such as described in AWS D20.1 or ASTM 52942.

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 and approved by the PAH. This should be verified by the part 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.
- Control of software revisions, automatic updates, and security

Configuration management of the qualified 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 7.

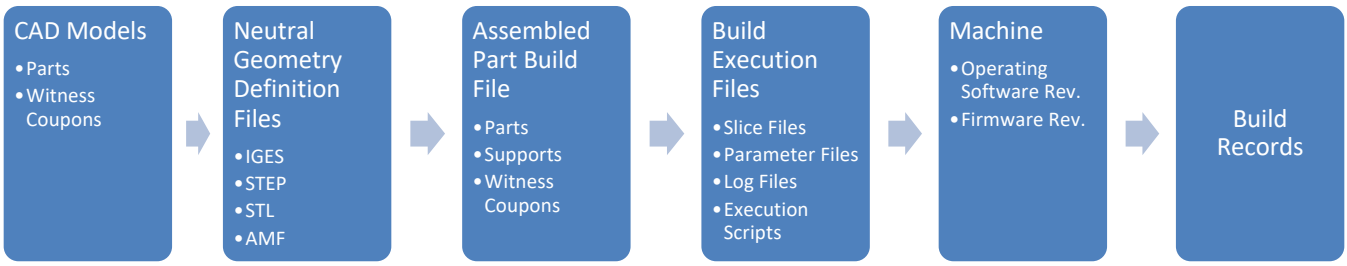

Figure 7: Software Requiring a Control Plan

7.2.2 Machine Qualification Plans

7.2.2.1 Key Process Variable (KPV) Plan

KPVs SHALL be determined through DOE or similar approach. The allowable range of values is used to define tolerance values. The tolerances should be shown to not impact the part performance in an

unacceptable way relative to the part requirements.

The DOE should address the criticality of the parts to be produced on the machine and their function. By conducting a part failure modes and effects analysis (FMEA) the KPVs that affect the critical function of the part can be identified. The part criticality may drive the need to assess and control specific KPV ranges/tolerances that affect material properties including durability and damage tolerance.

7.2.2.2 Machine Configuration Plan

All machines used for certified production 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 AM machine OEM and the part producer.

7.2.2.3 Preventative Maintenance Plan

All machines used for certified production SHALL have an approved, documented and tracked preventive maintenance plan/schedule. Aerospace parts will likely require a supplemental plan beyond the AM machine OEMs recommended maintenance plan. The extent and frequency of preventive maintenance may increase with part criticality to ensure machine settings and KPVs identified in the PCD remain within the possibly stricter control limit requirement. For example, L-PBF filters may be required to be replaced more frequently to maintain an acceptable KPV range for gas flow. Machine deterioration should be managed by SPC and/or included as part of the preventative maintenance plan.

7.2.2.4 Machine Calibration Plan

Machine calibration plan is defined by the part producer with KPVs and calibration frequency 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. The extent and frequency of calibration may increase with part criticality to ensure machine settings and KPVs identified in the PCD remain within the possibly stricter control limit requirement. For example, positional accuracy for stitched regions are likely to require more frequent calibration for critical parts. KPVs SHALL be defined by the part producer. Any measurement elements found to be outside defined calibration limits must be corrected, and any parts suspected to have been built using un-calibrated machine must be dispositioned via quality management system.

SAE AMS additive manufacturing process specifications provide industry accepted examples of calibration and verification plans for other additive manufacturing processes. One example set of calibration minimum measurement elements for L-PBF can be found in AMS7003, Appendix B.

A non-exhaustive list of calibration items is provided here for reference:

- 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

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 6).
- 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 6.10.3).

Machines used for manufacture of critical parts should have higher scrutiny for events that trigger machine requalification. Re-establishing qualification should also consider verification of process qualification for critical parts.

7.2.2.6 Feedstock Control Plans

As-received raw material documentation SHALL include certificates of conformance and meet any additional agreed upon requirements such as feedstock supplier internal specifications that control methods of manufacture of the raw material (powder or wire feedstock).

7.2.2.7 Feedstock Lot Control Plan

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

7.2.2.8 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.

7.2.2.9 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 described in Section 6.1. Additional requirements for used powder (e.g., blending, limits, handling and storage) SHALL be defined in feedstock material or process specification.

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 consolidated material performance requirements in accordance with part criticality
- 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

7.2.2.10 General Contamination Avoidance Plan

For powder bed machines, cross contamination of different powder compositions, within a machine or between machines or during handling or within tooling, SHALL be mitigated. Adjacent machines using different powder compositions should be physically separated or otherwise sufficiently isolated to avoid cross contamination. Cross contaminated feedstock powder and/or machine SHALL be dispositioned through the Material Review Board (MRB) process. It is recommended to work with a risk analysis of potential contaminations during all the process to define the best practices and control to ensure risk mitigation.

7.2.2.11 Machine and Material Alloy Change Contamination Avoidance Plan

Prior to introducing a change in feedstock composition to a machine, a deep clean process should be executed to ensure removal of all residual constituent materials from machine surfaces exposed to feedstock. It may be more economically pragmatic to limit each powder bed machine to one powder specification during its production lifetime, particularly for critical parts due to difficulties controlling and verifying cleanliness.

7.2.3 Part Production Plans

7.2.3.1 Engineering Requirements Flow Down 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 design applicant or DAH.

7.2.3.2 Manufacturing Build Definition Plan

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

7.2.3.3 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. Note that build parameters for a nested configuration may need to be adjusted relative to a single part configuration in order to maintain part performance.

7.2.3.4 Build Interruption Plan:

Planned build interruptions whether triggered manually or automatically may be allowed, but the restart procedure SHALL be included in an approved PCD. All other build interruptions SHALL be dispositioned in an MRB review. MRB considerations should include, but not limited to, the following in accordance with part criticality:

- The effects of interruption on material performance are demonstrated to meet consolidated 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 planned build interruptions that exceed the PCD allowance.

7.2.3.5 Quality Control Plan

The elements of the quality plan requiring process control SHALL be maintained as part of a PCD. Refer to Sections 12-14 for discussion on quality controls.

7.2.3.6 In-Process Monitoring Inspection Plan

In-Process Monitoring Technologies associated with additive manufacturing processes are developing at a rapid pace. An in-process monitoring technology may either be passive for simple reporting or could be a more complex active feedback control on the process. 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 component yield. For example, passive monitoring of the presence of certain manufacturing anomalies could be reported as a location to be assessed by NDI during final part inspection. Caution should be taken when developing active feedback control processes intended to enhance part performance because the means for validating such a system is quite challenging. These systems should not be confused with the full quality control plan, which includes final component validation. Reference Section 14.3 for discussion on in-process monitoring used for part inspection.

7.2.3.7 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
- Traceability record to calibration control, digital control, and build quality plans
- PCD revisions
- Feedstock lot, and certificate of conformance (CoC)
- Part fabrication records, including:
    - Machine-generated build reports
    - Planned Build Interruptions
    - Unplanned Build Interruptions
    - In-Process Rework
    - Post-Processing Variables
    - Inspection Records
    - AM Machine Operator Qualification Records
    - MRB Items
- Machine qualification records, including:
    - FAT
    - IQ
    - OQ
    - PQ
    - Maintenance & Calibration

7.2.4 Post-Process Plans

Common post-processing specifications or requirements 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 Performance Qualification (PQ)

Performance Qualification (PQ) is established after machine qualification (IQ and OQ see Section 6.10), material qualification (MQ see Section 8.1), demonstrating conformity to specifications and PCDs, by demonstration of process repeatability over multiple builds based on statistical data, and culminates with the successful completion of first article inspection. Qualification requirements are defined by the design applicant or DAH (Also see Part Design/ Qualification Processes). PQ occurs when the process is qualified to the part requirements on a specific machine serial number. Each machine serial number SHALL be qualified independently. The process is fixed once PQ is complete. The PQ SHALL be defined in and implemented by the PCDs.

7.3.1 Maintaining Performance Qualification (PQ)

Any change that requires machine requalification (see Section 7.2.2.5), or that can affect PQ requirements, SHALL necessitate requalification of PQ. Requalification of PQ may include elements of OQ and portions of the initially approved PQ performance requirements.

7.3.2 Qualification of Multiple Machines

When more than one machine is required to meet production demand for a part, at one or more part producers, some qualification efficiency is possible by using the PCDs established by the first machine. It SHALL be ensured that all machines have successfully completed the full PQ.

Machine equivalency is established when the null hypothesis (H0), which assumes that a machine is different when considering the performance standard required by the target applications (e.g. material specification, allowable, or design value), is rejected, based on statistical comparison of data from the candidate machine with the approved performance standard. In other words, machine equivalency is established when it is demonstrated that the performance standard on the candidate machine is equivalent to the existing approved performance standard based on statistical comparison of data. The extent of the performance standard to be demonstrated will vary with the design applicant or DAH design philosophy and application specific requirements (see Section 10).

MATERIAL PROPERTY DEVELOPMENT

8 Design Data Development

Material allowables and design values are needed by the design engineering and analysis staff to enable practical and cost-effective 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 verification. The rigor in material property development may be influenced by the part requirements, criticality and overall risk associated with the parts usage and regulatory requirements (i.e. certification basis).

The design applicant SHALL account for sources of potential variation throughout the materials science continuum, shown in Figure 4, in the development of design values; including variations in material characteristics and interactions between these sources of variation.

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 such as those accounting for the operating environment. Figure 8 illustrates this approach for static material allowables and design values.

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.

The authors of this document do not attempt to educate the reader on how to perform static, durability, and damage tolerance analyses, but rather highlight the conditions, features, and artifacts one should consider when creating these allowables and data sets.

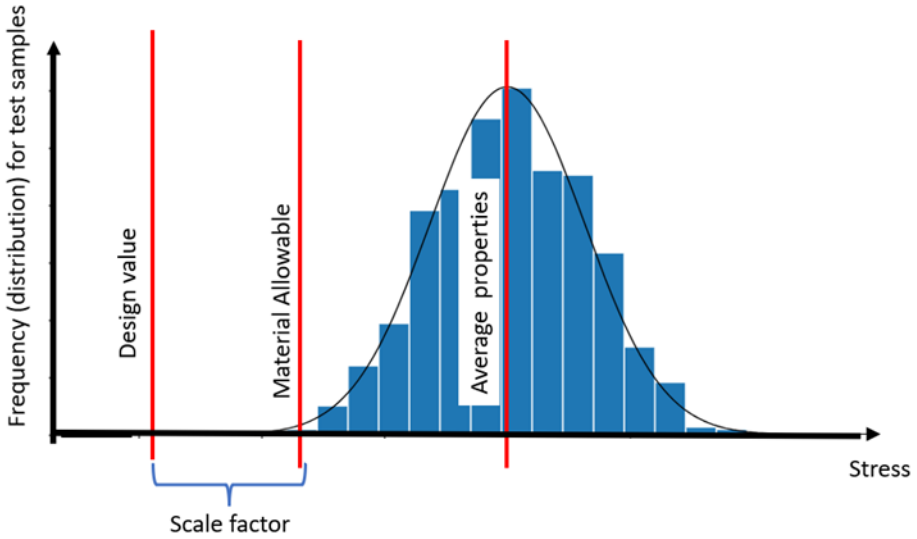

Figure 8: An Illustration of Material Property Frequency Distribution

The foundation for material allowable and design values is to characterize the material made under production conditions. 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. Legacy material allowable are typically only representative of generalized bulk material capabilities. Material allowable and design values should be representative of sources variation allowed by the specifications, see Section 8.1.

Conventional ASTM specimens may not always be appropriate for assessing certain material allowables and design values. In some circumstances, there may be a need for new coupon configurations and specialized test methods. The use of non-standard specimens and specialized test methods SHALL be validated, ideally by comparison with standard test methods and specimens, and shown to be representative of the applicable material characteristics or design features. The effect of non-standard test specimen geometry may shift the data set when compared to standard geometry specimen test data and therefore should not be combined.

Definitions of commonly used terms, such as material allowables and design values, and their range of applicability, are provided in Appendix A – Definitions and Terms. All material allowables and design values SHALL meet the regulatory requirements (e.g., engines, propellers, aircraft) and internal quality standards prescribed by 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 property 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.

When developing the material property test plans, it is important to understand the anomaly distribution inherent to the fabrication process and the anomaly detection capability of the planned production process inspection method. The design data used to determine the defect limit may be reached via process limitation and part features. Inspection techniques and detection limits SHALL be validated see Section 14.1.

The performance of parts may be sensitive to anomalies that are below the limits of detectability of the inspection method system available. When the planned production inspection method's detection capability is higher fidelity than the anomalies (size / shape/ location /density) captured in the design data, anomalies detected need to be assessed against specification acceptance limit. Those above the limits are considered rejectable defects and need to be submitted to MRB for disposition. See Figure 9 Detection Capability A. When the detection capability of the planned production inspection method is consistent with the anomalies captured in the design data, all detectable anomalies are characterized as defects and submitted to MRB, see Figure 9 Detection Capability B. If the detection capability of the planned production inspection method has less fidelity than the anomalies captured in the design data, the inspection may only be acceptable if the design applicant has demonstrated that the process is unlikely to generate anomalies more severe than the anomalies size/ shape/ location/ density captured in the design data, see Figure 9 Detection Capability C. An inspection plan SHALL be defined and explained to mitigate the risk of anomalies that could impact the material properties. Part inspection plans may be paired with process inspection methods, for example, destructive analysis of coupons to see the potential deviation on destructive inspection or periodic part cut up with higher capability detection.

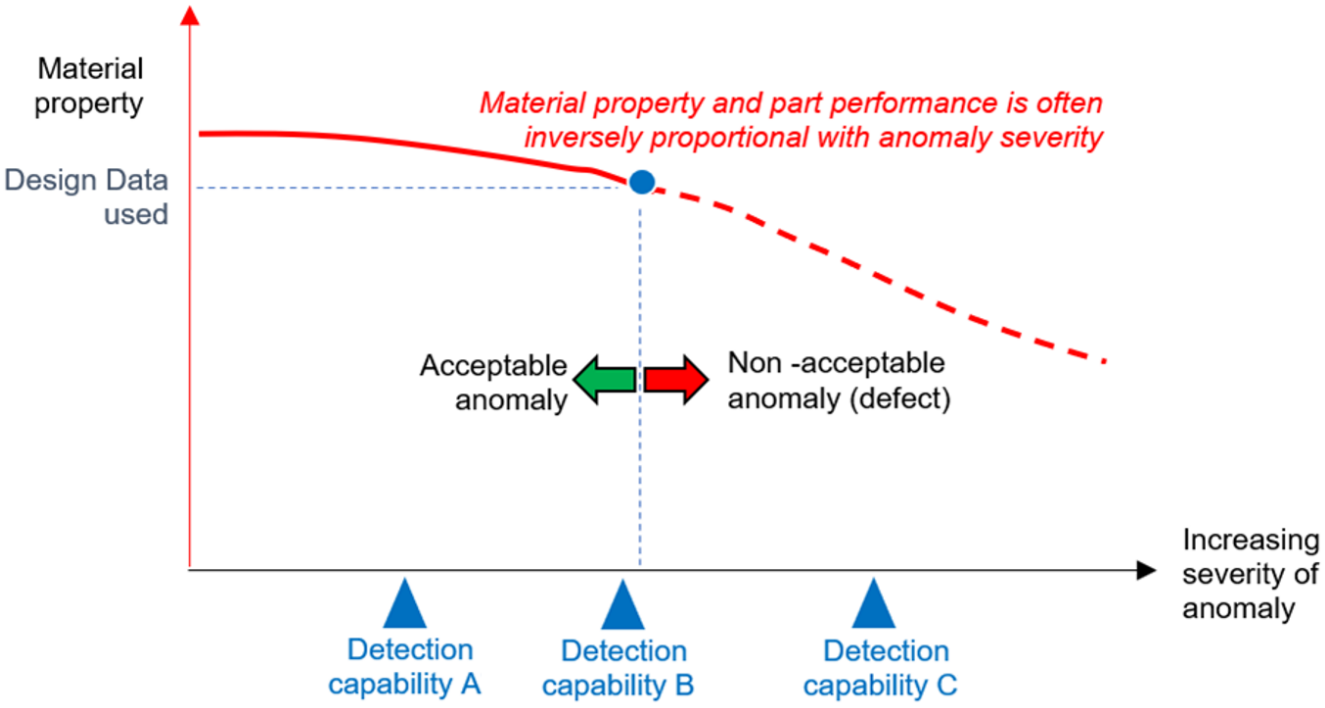

Figure 9 Relationship of anomaly detection to design data

When developing design data there are many potential strategies to satisfy regulatory requirements. Caution should be taken when selecting detection capability C as depicted in Figure 9. This approach is not recommended for critical parts. For high critical parts, in addition with the inspection plan described, it must be demonstrated that the process doesn't generate anomalies more severe than the anomalies size/ shape/ location/ density captured in the design data. The influence of sub-detectable anomalies on part performance and continued airworthiness may drive a difference in certification approach. Examples of such approaches include but are not limited to or a combination of;

1) Gain in service experience with less critical parts, demonstrate similarity, and incorporate lessons learned
2) Data driven knockdown factors on material data
3) Physical testing of components with intentionally embedded smallest detectable defect at most critical locations or effect of defect study of specimens
4) Crack growth analysis simulations using validated models to establish threshold and repeat inspection intervals for continued airworthiness
5) Risk based probabilistic analysis and zonal analysis
6) Additional approaches for certification by test or verification testing are discussed in Sections 10.2 and 14.4

8.1 Material Qualification (MQ)

A prerequisite for generating bulk material design data is the development of a repeatable and robust manufacturing process system defined by approved or controlled preliminary material and process specifications. Preliminary property data may be created once OQ (Section 6.10.3) has been completed. Key property data critical to part performance SHALL be demonstrated from every machine after PQ (Section 7.3). Design data will either be part of an approved public or proprietary

database or developed at the time of need. It is unusual for a test plan to generate a comprehensive material data set that fully covers all potential design applications, rather it is more likely that bulk material design data are developed for a specific design application and then expanded as more design coverage is needed. The test plan should also address all relevant build directions and features that use the same machine parameters/thermal history. MQ is complete once the minimum material data set is defined or verified, refer to Figure 2.

Sources of variation that may contribute to material characteristics (e.g. microstructure, anomalies within acceptance limits, and residual stresses) that SHALL be evaluated include, but are not limited to the following:

- Feedstock material lot to lot and supplier to supplier
- Powder reuse (see Section 7.2.2.9). 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.
- Build cycle to build cycle
- Machine to machine (or parameter set to parameter set)
- Heat treatment lot
- Effect of differences occurring spatially throughout a build due to thermal history, scan or deposition strategy, inter-pass temperature, or gas flow, etc. (i.e., location in build volume).
- Substrate integration into final part and heat affected zone
- Process drift of KPVs at limit of tolerance band (local)
- Design features enabled by additive manufacturing

Note: Incorporating data from the limiting reuse may create a bi-modal distribution in the collected data which will either prevent the derivation of allowables or be censored out of the data from which the allowable is derived. The design applicant needs to determine an acceptable compliance approach for developing allowables with this type of data set.

A test matrix should be defined considering relevant sources of variation, including those defined above. The interactions among these variations should also be accounted for. 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.
- 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 material allowables will be determined to be either isotropic or directionally dependent.
- Effect of cross-sectional thickness is best captured by tests of a range of thicknesses representative of the part applications. The scope of thickness ranges to consider should be relative to the microstructure produced by the process.

Unknown sources of variations or any unknown magnitude of variations may need additional quantification when applied to critical parts. These sources of variations may be further understood and quantified by gaining in-service experience with lower criticality parts.

AM can enable complex designs that may make inspection and engineering analysis more difficult, and failure modes more complex. Complex failure modes can be introduced at a design level, material level, or processing level. Geometric complexities can introduce complex loads paths and load redistributions upon

progression of failure and multistage failure progressions, like multisite and widespread fatigue damage (MSD and WFD), introduce multiple failure modalities. The ratio of wall thickness or lattice member to grain size and relation to orientation may be a factor to consider in these failure modes. Process complexities introduced by residual stresses from thermal gradients or chemical and mechanical impacts of surface finishing methods may create non uniform performance across the geometry. Additive manufacturing can enable more unitized structures, novel crack arrestment features, advanced cellular and lattice structures, or functionally graded material. When introducing novel design philosophy, the certification approach must consider these complex design features and each unique failure mode during the development of material allowable and design value test plans.

Detection limitations of the inspection method should be able to detect the defects that exceed the characterized anomalies included in material property development. In the case that inspection detectability limits are not capable of resolving the anomalies characterized, then the design data development must account for the uncertainty of performance in this regime. When the scale of the print is on the same order as the scale of inherent anomalies, for example thin-walled lattice, features may not be detectable and therefore need to be accounted for in material property or design value development.

When the certification approach includes development of scale factors (i.e. data driven knockdown factors), these factors can be developed in a four-step process. This approach may not be applicable if design data already incorporates these factors.

1. Conduct non-destructive inspection of material allowable test articles and other developmental parts to establish the probability of detection (POD) for candidate inspection methods, to define acceptance limits for each type of anomaly and decide which inspection method(s) will be incorporated into the material and process specifications and/or part design.
2. Conduct metallography and fractography of anomalies present at the failure surfaces of test articles used to develop material allowables, to identify and define the various types of anomalies and their morphology (shapes), size(s), and location(s) and statistically account for these anomalies in design data. This statistical analysis is typically used to define the NDI and destructive inspection criteria.
3. Connection to part:
    a. Validation of non-destructive inspection methods and POD of the candidate part to Step 1, see Figure 9 for additional information.
    b. Conduct assessment of Step 2 on a representative part for coupon to part consistency of morphology and inherent population of anomalies to the part level. See Section 9 for additional information.
4. Develop factors that analytically account for effects from the difference between anomalies which are accounted for in design data and those which are allowable by process. Developing factors via analysis SHALL be validated by correlation of the analysis with test.

When the certification approach includes crack growth analysis simulations or data driven, risk based probabilistic analysis the design data must be obtained using the guidance provided in Section 8.1.2.

8.1.1 Material Allowables Development

For the purposes of this document, material allowables are limited to static properties, as defined in Appendix A. Material tested for the development of material allowables must be produced on qualified machines and process (Section 7.3). Material allowables SHALL account for the sources of variability noted above (Section 8.1). Volume II of The Metallic Materials Properties Development and

Standardization (MMPDS) Handbook is a source for process intensive metallic material data generation and analysis guidelines which will include material allowables in future editions as data is submitted, analyzed by Battelle Memorial Institute, and reviewed and approved by the MMPDS General Coordination Committee meeting. Note *"In the context of this Handbook, further showing means providing additional evidence for validating the applicability of MMPDS material allowables to a specific certification criterion or application, the extent of which may vary with application and the regulatory authority's requirements."* It is common for a design applicant to develop proprietary material allowables which are subject to regulatory review as a part of the certification pathway. *"Further showing requirements for proprietary allowables for process intensive metals will be determined by the government regulator."* Conventionally, statistically based material allowables are developed using fully machined coupons that are either purpose-built or excised from pre-production components or generic shapes, using industry standard coupons and test standards. Coupons that are not machined due to complex or thin wall part features may be sensitive to surface conditions and therefore are not material allowables and rather should be included in design value development.

8.1.2 Durability and Damage Tolerance Data Set Development

Durability and damage tolerance data sets can support a variety of end uses, as required by regulation, economic needs for reliability, or individual design applicant design philosophy, and may influence the scope and type of data package developed. For purposes of this document, fatigue, crack growth and fracture toughness material data sets are utilized in durability and damage tolerance design data development, as defined in Appendix A – Definitions and Terms. Note: FAA standards use **Fatigue** & Damage Tolerance (F&DT) to emphasize certification safety, while DoD practice generally uses **Durability** & Damage Tolerance (DaDT) to highlight sustainment and lifecycle performance. "Durability" reflects a broader sustainment perspective that includes not only fatigue cracking but also corrosion, wear, and long-term reliability and service life considerations.

Design data used in durability and damage tolerance analysis may be derived using a variety of industry or proprietary standard procedures with associated scale factors. Durability and damage tolerance properties are prone to a high degree of variability therefore methods of analysis must account for scale and scatter.

The characterization of additively manufactured components may differ from that of conventional products. These differences should be considered before assuming that traditional product behaviors apply and must be understood by the design applicant. The durability and damage tolerance data sets must account for the components in the as used condition after all manufacturing, assembly and installation process steps.

Difference in AM features and artifacts that should be considered include but not limited to:

- Microstructure
- Geometric features
- Defect morphology and their distribution
- Surface roughness, morphology, and variation as built and/ or final component surface (See Section 6.6.6)
- Inherent process anomalies
- Residual stress distribution and mitigation strategies (see Section 6.6.2)
- Performance of chemical post processing and coatings (See Section 6.6.7)
- Post printing chemistry
- Post processing impacts: support removal, depowdering techniques, and component extraction

- Thermal exposure history throughout the build

These features and artifacts unique to additive manufacturing may impact the following aspects of durability and damage tolerance analysis; corrosion, stress corrosion, wear and tribology, corrosion fatigue, stress fields, stress level and stress ratio effects, susceptibility to embrittlement, starting flaw size assumptions, multi-site damage scenarios, cracking patterns, crack growth rate and interaction, inspection type and capability, multimode behavior, scatter, time to initiation, damage coalescence, and microstructural mechanics failure. This list is non-exhaustive and will be subject to the verification and validation of the design applicant.

Development of test programs to generate durability and damage tolerance data sets must account for the features above. Due to the uniqueness of additive manufacturing in the above features industry standard coupon types may not address these factors and need development and validations.

8.2 Design Value Development

Design values are typically derived by applying scale factors to average / typical test data sets or statistically based material qualification data. Depending on part application, part performance and criticality, design values may be needed for static, fatigue and/or damage tolerance evaluations which may be derived using a variety of industry or proprietary standard procedures.

The development of design values data SHALL account for any geometric feature, location in the part, environmental effects, or post-processing that may result in design values that differ from the material qualification data (bulk material properties). This may involve testing at various levels in the meso-scale (coupon, core elements of design, or part level), see Figure 3. KPVs used to build coupons or core elements of design should be shown to be representative of the part(s) feature(s) for which design values are being developed. Examples of design value considerations include, but are not limited to:

- Thin wall section which deviates in material performance from the material qualification data
- Any feature, complex part geometry, location or orientation where the microstructure, anomaly distributions or mechanical properties vary from the material qualification data
- 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).
- Surface condition, both as built and post processed, as well as finish coatings
- In service environmental factors
- Production environmental factors (vibration, temperature, humidity, etc)

Similar to other manufacturing methods, design values for additively manufactured parts must account for secondary effects of chemical, mechanical or thermal treatments and their interactions. For example, residual etchant remaining on the part after fluorescent penetrant inspection or oxidation after heat treat could adversely affect part fatigue life. To develop part specific design values, the design

applicant needs to demonstrate that the test specimens accurately represent the properties of the finished part, ideally by comparison with individual parts and shown to be representative of the applicable design feature. These specimens need to use the same feedstock specification, process specification, PCD (including KPV settings and values), and post-processing including thermal treatments, machining, and surface enhancements as the part being certified. Part specific design values account for attributes of the parts they represent, including but not limited to surface conditions, similar anomaly types and characteristics, microstructure, and hardness. The placement, quantity, and orientation of the specimens are determined to provide accurate representation of part quality.

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. Conventional ASTM specimens may not always be appropriate for assessing certain design data. In some circumstances, there may be a need for new coupon configurations and specialized test methods.

The type of test specimen should be selected based on the behavior being assessed. For example, notch specimens may capture only localized material behavior which is not adequate when assessing the effect of anomalies distributed throughout a larger volume. A constant gauge specimen is more suitable to evaluate the impact of a larger volume of material, especially when evaluating dynamic properties.

8.2.1 Single Part Material Data Generation

Generation of relevant material properties and design values that have only been evaluated against single part's specific requirements is a key element of a point design approach. This may be accomplished with limited engineering effort covering 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. While point design may be an entry point due to the above considerations, it is likely not economically viable for adoption of multiple parts. A company may often start with this approach and although these design values are limited to a single part number, they can be expanded upon, forming the basis for the development of material allowables with a broader application space.

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 can be more efficient than creating unique allowables and design values for every part. Guidance material for part families is being developed by ASTM F42.07.01 subcommittee.

Expanded applicability may be achieved by an engineering equivalency approach. This could be achieved by pooling test data which reflects additional part designs and features, environmental factors, as well as differences in material and process parameters. However, prior to exercising an engineering approach to equivalency, there must be significant commonality in the design features and process parameters which may affect the important failure modes. If these conditions are satisfied, assessment can be made to determine whether test data from additional part number(s) may be pooled. Care must be taken when attempting to apply an engineering approach to equivalency for additional part designs and features because the true effect of such differences can be difficult to detect using small sample

sizes. It is the responsibility of the design applicant to demonstrate sufficient level of similarity for all parts within the part family relative to the design values of interest.

Use of a part-family approach still requires the same OQ of the material. They SHALL have the same:

- Feedstock material specification, including grade and class of the feedstock, if applicable.
- AM process specification.
- Consolidated material specification.
- PCDs, with the exception of part geometry.
- Additive material post processing (e.g. thermal treatments).

If using existing material allowables and part design values, the same PQ SHALL be used to qualify the material including engineering equivalency to the existing approved additive mechanical properties including design value scale factors (e.g., fatigue with surface roughness, thin walls, notches, part size, etc). It is expected that critical parts, which may have more complex failure modes and build sensitivities, will require more scrutiny to demonstrate equivalency to be included in a part family.

PART DESIGN CERTIFICATION PROCESSES

Performance Qualification of the part SHALL include process development as addressed in Section 6, supply chain qualification as addressed in Section 7. Material Qualification and design data development as addressed in Section 8. These items are in support of showing compliance for part certification.

9 Verification of Design Values

The material allowables and design values established in Section 8 allow the design engineer to select the appropriate material and material properties to use in developing part designs. It is necessary to verify the individual and combination of all appropriate scale factors (see Section 8.1.2) and design values that have been applied to the part do indeed envelope the application's intended use. Care must be taken to identify and adhere to the limits of applicability of each design value and scale factor.

10 Detailed Design Requirement Verification

Certification approaches, as agreed with regulators, may include analysis supported by test or testing alone. Prior to a part being released for manufacture, the design SHALL be approved or qualified. Depending on the application, a property specific scatter factor may need to be defined specifically for AM for potentially higher scatter compared to conventional fabrication techniques.

10.1 Certification by Analysis Supported by Testing

Design 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. Predict part performance (e.g., static properties, predicted life, and/or damage tolerance assessment) with scale factors
6. Retain fixed digital models of the final part

Finite Element Analysis (FEA) and/or testing is commonly used to determine worst case stress conditions. Factors that conventional FEA do not capture such as surface finish, material factors (e.g. environmental degradation, grain growth, temperature) must be accounted for in the design values and material property inputs for strength and stability checks within the FEA. 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 verification is complete when all requirements have been shown to meet the associated design value. Figure 10: Design Margin to Design Value Illustration illustrates this approach for static properties.

Additive manufacturing materials represent a complex ecosystem that also affects the level of modeling complexity such as residual stress states, novel geometry and load paths, anomaly distribution, inherent anisotropy and heterogeniety of properties. Organizational maturity and successful experience for the use of modeling and simulation with a certification by analysis approach should be considered when deciding on the extent of use of modeling and simulation in certification process, including consideration of associated risks and applicable prior successful correlation of failure modes and failure loads. Applicants are expected to demonstrate a comprehensive showing of compliance.

10.2 Certification by Testing

In cases where parts that don't lend themselves to analysis or inspection through geometric restrictions or low volume production, there are cases where part certification by test is a preferable route to show compliance. As an example, because of the size or geometry of a part, interior portions cannot be inspected non-destructively, a certification test can be used to safisfy the cert basis of the part. A test methodology needs to be developed to certify by test and agreed with regulators as a methods of compliance, this then becomes the basis for conformity in production(reference Section 14). The degree of demonstration by test to show compliance is commensurate on the criticality of the part as agreed with regulators. Through certification by test, scale factors are not fully understood without the "pyramid approach". Testing will have to account for scatter of material/ process variation not developed, failure modes, loads, environment, and other unknowns. Functional testing to failure, such as loads above ultimate, should have consistent failure locations and failure modes. One approach to account for variability is by applying over test factors to demonstrate design acceptance.

A possible example of certification by test would be a radiator/heat exchanger part. The functionality of the part can be more easily shown than NDI of an interior lattice of radiating fins. One can pressure test the component commensurate with its structural criticality, higher than nominal pressures, and demonstrate the part meets required certification basis.

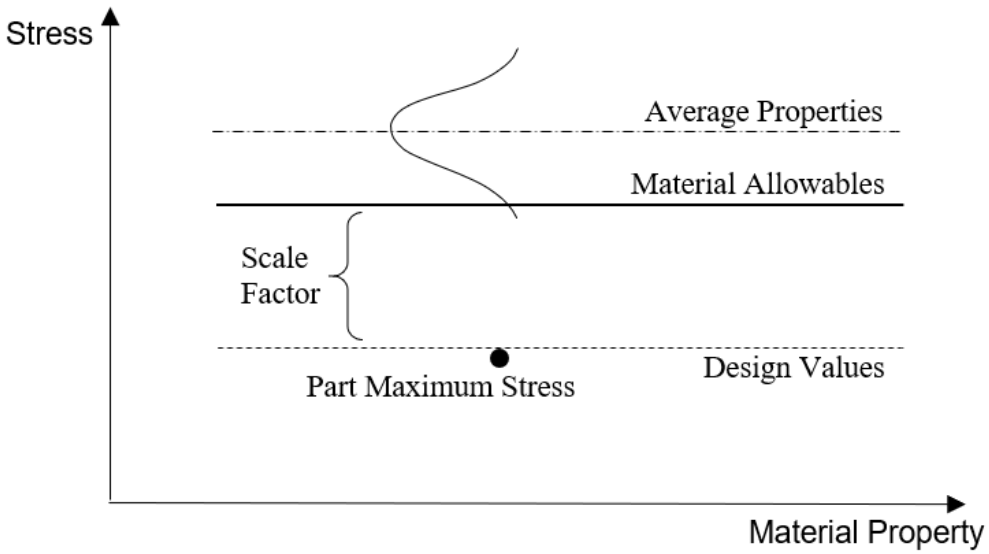

Figure 10*: Design Margin to Design Value Illustration*

11 System Qualification

System qualification is 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. System in terms of this section is intended to address the sub-assembly and component macro scale of Section 5.3.

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. The intersection of part function, criticality, and process failure modes may drive additional failure modes and effects analysis (FMEA) for higher criticality parts. 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, corrosion and environmental considerations, assembly methods, vibration harmonics, secondary cooling flow, fluid contamination, detached powder surface particles during part life (with vibration, thermal expansion) and other functional interactions between components of an assembly should be considered and tested to ensure 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. The continued airworthiness plan needs to be considered at the system level including reliability and possible failure modes unique to AM. 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. Although AM presents unique considerations that must be addressed as described throughout this document, there is no difference in system level requirements.

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 completed part including all post processing inspection and test steps and determines the risks and potential modes of failure and consequences for each step, including potential effects on mechanical durability, corrosion and other properties important for the part[11]. 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 is developed from the part design and specification requirements to demonstrate that each part conforms to its requirements which may be verified by performing a first article inspection. The quality plan for a production build is a means by which every part is shown to conform to its 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 volume
- Type of test bar/ specimens on platform or build volume (also known as process control specimen, PCS)
- Geometry and surface finish of each test bar/ specimen
- Location of each test bar/ specimen
- Dimensional inspection plan
- Functional test plan

The quality plan can include non-destructive and destructive evaluation:

- Part cut-up plan and sampling rate
- Statistical Process Control (SPC) of key process variables
- Material properties such as tensile properties, fatigue properties, grain size, chemical composition, density extracted from part or from separately built Process Control Specimen (PCS)
- Non-Destructive Inspection (NDI)

Build sampling may be established based on the part producer's approved quality system. It is recommended that critical parts retain 100% sampling rate for select PCS of material properties until a stable process is established and a sampling plan can be determined, as example AS9103. Test methods for PCS varies by part criticality and material specification. Non-critical applications may include specimens for part or lot acceptance testing for material composition, tensile, and hardness as a minimum to verify the bulk material properties. Higher criticality part applications may include additional PCS for part acceptance testing such as fatigue, and fracture toughness as an example. In both scenarios the Quality Plan defines the number and type of coupons required for testing. The PCD will define the PCS locations, geometry, and orientations. Caution: PCS specimens are not necessarily representative of the part performance and generally not appropriate for design value development. PCS may be from an as-printed process or fully post processed state, including surface finish

11 AS13004 - Process Failure Mode and Effects Analysis (PFMEA) and Control Plans

condition, depending on key characteristics being monitored.

13.1 Statistical Process Control

Part production builds should have defined SPC/sampling plans and control charts for part acceptance and trend analysis appropriate to the intended part. As an example, control charts for KPVs, 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. For critical parts it is recommended to set process control limits stricter than non-critical process applications, such as Kpc 1.0 or higher. Out of control variations conditions may be cause for corrective action such as preventative maintenance (Section 7.2.3.5) prior to reaching a specification failure. Process control specimens (PCS) can be used to collect data in support of statistical process control. For example, hardness testing of parts or specimens during the heat treatment process can be used to verify conformance to the specification or detect any potential drifts in the heat treatment process, which can inform adjustment of time or temperature to maintain the process within control limits.

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. Additive manufacturing may have a higher rate of nonconformance, MRB allowances/ margins are recommended. 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 repair required for a component by the part producer (including un-planned build interruptions) SHALL be approved by the MRB. Refer to Additive Manufacturing (AM) Repair Facility Quality Requirements for Aerospace Application (AMS7061) for recommended quality requirement for repairs. See “Industry Guidance and Best Practices for AM Repair and Alteration within the MRO Environment” for guidance to MRO facilities for completing work on additively manufactured components.

14 Inspection and Verification Testing

The discussion of inspection in this context refers to supply chain inspection and covers topics related to the inspection of fielded parts. Inspection techniques to reliably detect and categorize anomalies are required as part of the production and life management processes, see Section 8. These techniques can include visual, geometric feature verification, leak testing, liquid penetrant, eddy current, ultrasonic, radiographic, infrared imaging, and 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 five categories:

- Material inspection
- Dimensional inspection

- In-process monitoring for part inspection
- Functional performance verification test
- In service inspection

14.1 NDI and Material Inspection

Non-destructive 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, dye penetrant inspection, fluorescent penetrant inspection (FPI), magnetic particle inspection (MPI), computed tomography (CT), etc.) are appropriate for materials of all manufacturing methods, including AM products[12]. Similar to castings, the as-printed surface roughness of an AM part can result in false indications when using FPI or MPI, which can be mitigated via surface enhancement (see Section 6.6.6). 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). Inspection method and acceptance criteria are dependent on the part criticality, application type (e.g., static vs. fatigue properties), as well as any part number specific requirements, and will be documented in the type design and assured though the build quality plan. Seeded defect studies and POD studies are often the methods by which the NDI technique is qualified. Caution: Certain anomalies, such as lack of fusion or micro-cracking, can be challenging to detect with current standard NDI methods. If anomalies cannot be reliably detected, then an alternate inspection method and quality plan is required, if an alternate inspection method is not available then an alternate Material Qualification study needs to be performed, see Section 8.1.

Conventional techniques for material inspections, such as microstructure, chemistry and coating performance evaluations, are appropriate for AM parts.

14.1.1 Anomalies and Defects

Additively manufactured parts may possess certain internal or surface features that are anomalous to the bulk structure. These features are an artifact of the manufacturing processes. The part requirements SHALL define acceptable limits for each of these anomalies and be documented in the type design and assured though the build quality plan. Only when these thresholds are exceeded is the anomaly then characterized as a defect and SHALL be submitted to MRB, see Section 13.2.

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 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.
- Balling is the instability of the molten material in the melt pool resulting in solidified spherical droplets on the build layer. This artifact can promote increased porosity and inclusions in subsequent layers.

12 NASA/TM−20220013820 A Survey of NASA Standard Nondestructive Evaluation (NDE)]

- Surface condition refers to the surface morphology and roughness.

14.2 Dimensional Inspection

Verification to dimensional requirements by the part producer is closing the loop from component requirements across the full supply chain. Each production applicant SHALL ensure that every part from every machine will meet its design requirements. In general, this is a 100% dimensional part verification. This is typical of a first article inspection 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
- Surface roughness measurement

Note: conventional profiler roughness parameters, such as Ra, may not be appropriate to characterize as-printed surfaces. If characterization of the surface is essential, it is recommended to consider other inspection methods or metrics. A number of alternative methods and metrics are currently under investigation (e.g. optical profilometry or roughness parameters, such as Sv).

14.3 In-Process Monitoring for Part Inspection

In-process or in-situ process monitoring of the process may occur in specific stages of the production process. The build process on a machine may include in-process monitoring systems to adjust the build during printing (closed loop control) or to trigger additional post build inspection requirements (open loop). In-process monitoring technologies are maturing and caution should be taken prior to application. The current typical use of this technology is limited to passive monitoring and post build verification. When in-process monitoring systems have been matured to a point of use as a means of inspection, these systems SHALL be properly validated, maintained, and qualified.

Additional guidance can be found within ASTM E3353 Standard Guide for In-Process Monitoring Using Optical and Thermal Methods for Laser Powder Bed Fusion, the ASTM Strategic Guide: Additive Manufacturing In-Situ Technology Readiness Report, and 6th /7th Joint EASA-FAA Additive Manufacturing Workshop (2023/2024): Machine Monitoring Working Group – Developing a Five-Year Plan to Allow EASA / FAA acceptance roadmap.

14.4 Functional Performance Verification Test

Functional performance requirements are specified when conventional inspection methods are not achievable or can only be performed by specific tests to verify key requirements. The functional performance test may be performed on an individual part using methods such as flow testing of internal non-inspectable flow channels, proof pressure, or leak testing. Components comprised of an

assembly of parts may include structural proof load tests, leakage tests, or a series of functional tests to verify the final functionality of the component. Various standards have been published for functional testing of components for aerospace applications.

The higher the criticality of the part may increase the level of functional performance testing required to verify the part performance and satisfy the safety requirements of the applicable certification basis. The tolerance of key performance characteristics may tighten with criticality. An example is the more stringent part cleanliness for a component located in a critical flight control hydraulic system. Care should be taken to address the risk of residual powder that could block flow channels or create foreign object debris (FOD).

As experience with the part and the fabrication method is developed through test data, the number of parts per production batch to be tested may be reduced when an approved quality control procedure is established to the satisfaction of the regulator or DAH.

14.5 In-Service Inspection

Selection of in-service inspection methods may be limited compared to production inspection methods and may not be available on the fielded aircraft. These limitations should be accounted for in part design, verification processes, and continued airworthiness plan. The selection of in-service inspection methods must additionally consider anomalies resulting from maintenance or operationally induced damage (e.g. accidental damage, corrosion, fatigue cracking) or a part replacement strategy may be needed.

Inspections performed when an additive manufactured part is in service as a part of continued airworthiness plan may face the same challenges with anomaly detection. Inspection acceptance limits may be different than production inspection acceptance limits. As discussed in Section 14.1, surface modifications may mitigate surface roughness and aid in service inspections. For example, standard calibration specimen may not be representative of the additive part for inspection, and a revised NDT reference specimen may need to be developed. Like other integral design parts, some additive manufactured designs may face challenges in accessibility for inspection, i.e. topology optimized parts, part integration, internal cavities, conformal part assemblies, etc. These challenges of additive manufactured design may benefit from the developments in health monitoring inspection techniques to increase part assurance while in service, however monitoring and predictive methods are evolving, and advancements are still needed for practical use.

15 In-Service Repair

The scope of this document is focused on the development, qualification, and certification of additive manufactured parts installed on certified products (aircraft, engines, and propellers) regulated by 14 CFR Part 21 and respective type regulations. In service part repair, alteration, and replacement require a thorough understanding of the design, manufacturing process, and material requirements as discussed in the previous sections. The relationship between the type certificate holder, fielded aircraft, and regulations pertaining to maintenance and repair are covered in the guidelines referenced in “Industry Guidance and Best Practices for AM Repair and Alteration within the MRO Environment”.

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 industry's current 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, certification may be achieved using established and proven methodologies as a baseline, supplemented with additional focus on issues unique to AM.

APENDIXES

16 Appendix A – Definitions and Terms

16.1 Definitions

For the purpose of this document, the definitions below are utilized as guidance.

Anomaly: An imperfection or discontinuity that may be detectable by non-destructive testing and is not necessarily rejectable. ASTM defines this as flaw or discontinuity.

Component: Any self-contained part, combination of parts, subassemblies, or units, that performs a distinctive function necessary to the operation of the system.

DAH: The organization that holds a design approval issued by the FAA. Analogous to the design organization which holds a Design Organization Approval (DOA)

Damage Tolerance: Damage Tolerance: The attribute of the component that permits it to retain its required residual strength without detrimental structural deformation for a period of use after the item has sustained a given level of fatigue damage, environmental damage, manufacturing defects, accidental damage, or discrete source damage.

Defect: An anomaly that does not meet established acceptance criteria.

Durability: The ability of a material or component to maintain its intrinsic strength and other functions in service over an extended period due to operational use (such as fatigue and thermal loading, or accidental damage, environmental exposure, impact, or contact) resulting in wear, cracking, deterioration, or other types of damage. Examples of threats to durability can include corrosion, erosion, fatigue, corrosion fatigue, SCC, wear, widespread fatigue damage, etc.

Design Value: Material properties that are established from test data and represent the finished part properties. Design values may be established on a statistical basis or typical basis. These values are usually based on material allowables and adjusted by using scale factors, 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). For purposes of this document, fatigue, crack growth and fracture toughness test data sets are also utilized in design value development.

Fatigue: Fatigue refers to the weakening or damage of a material or structure over time as a result of repeated or cyclic loading (or a series of alternating load reversals).

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. This paper does not distinguish between the more precise terms Key Parameter (KP), Key Process Parameter (KPP), Key Process Input Value (KPIV), Key Process Output Value (KPOV), and Key Process Variable (KPV).

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. For purposes of this document, material allowables are limited to static properties.

Material Property: The characteristics of a material. Other factors may need to be considered to use

property values in design.

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.

PAH: The holder of a PC, PMA, or TSO authorization, who controls the design and quality of a product, article, or part(s). A person who has been issued a production approval by the FAA. Analogous to production organization which holds the Production Organisation Approval (POA).

Part: An additive manufactured part or singular component.

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

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

Process Control Specimen (PCS) – A process control specimen is a test specimen associated to the additively manufactured material and process intended to demonstrate process repeatability over multiple build cycles through statistical process monitoring (SPC). These specimens are typically separately built or attached to the part during build and removed for analysis. Process Control Specimens may be known in the industry as witness coupons, prolongs, lot acceptance coupons, etc.

Reliability: The probability that a material or component will perform its intended function without failure for a specified period of time and under specified conditions.

Scale Factor – Typically, a numerical debit against a material allowable or average property associated with part specific features and actual conditions such as operational, manufacturing, design, environmental, service history, reliability, and safety considerations. In some cases, it represents a credit such as in the case of cold working or peening.

Scatter Factor – 25.571 definition: a life reduction factor used in the interpretation of *fatigue analysis and fatigue test results.*

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 in this document when a best practice is recommended but not required. 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 PAH.

Type Design: See CFR 14 Part 21.31.

Typical Property: A typical property value is an average value and has no statistical assurance associated with it.

16.2 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

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

FMECA - Failure modes, effects and criticality analysis

FPI – Fluorescent Penetrant Inspection

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

NDI – Non-Destructive Inspection

OEM – Original Equipment Manufacturer

PAH – Production Approval Holder

PBF – Powder Bed Fusion

PCD – Process Control Document

PFMEA – Process Failure Modes & Effects Analysis

PMA – Parts Manufacturer Approval

POD – Probability of Detection

PPE – Personnel Protective Equipment

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

SPC – Statistical Process Control

STL – Standard Tessellation Language

WG – Working Group

17 Appendix B - Contributing Individuals and Organizations

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