WHITE PAPER

ADDITIVE MANUFACTURED AVIATION PARTS

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SCOPE

This document references, aggregates, and summarizes existing requirements for qualification of Additively Manufactured components. This document only applies to components that will be installed on an aircraft.

This document is intended to provide general guidance for a Program Manager or a supplier to understand the qualification requirements to establish and maintain airworthiness for Additively Manufactured components. The following AMACC sections contain requirements that would need to be tailored for qualification of a specific component:

a. Section 4 Systems Level Requirements, Processes and Engineering Cognizance

b. Section 5 Structures

c. Section 7 Propulsion and Propulsion Installations

d. Section 14 System Safety

e. Section 16 Sustainment of Airworthiness

f. Section 19 Materials and Processes

BACKGROUND

Advanced Manufacturing (AdvM) refers to activities that depend on the use and coordination of information, automation, computation, software, sensing and networking and/or make use of cutting-edge materials and emerging capabilities enabled by the physical and biological sciences. It encompasses new ways to manufacture existing products and the manufacturing of new products resulting from advances in technology. It includes, but is not limited to, additive manufacturing (also known as three-dimensional (3D) printing).

Additive Manufacturing (AM) is the process of joining materials layer by layer to make objects from three-dimensional models. This is in direct contrast to traditional methods of manufacturing, such as machining, which are subtractive by nature. AM can provide benefits such as weight reduction, reduced lead time, and complex component geometries that are difficult to manufacture using traditional methodologies. Families of additive manufacturing are included here. AM is a rapidly evolving technology, and new methodologies may or may not fall within these families.

Binder Jetting

An AM process in which a liquid bonding agent is selectively deposited to join powder materials. This method does not employ heat to bind materials. Typical materials include

metal, polymer, ceramic or sand.

Cold Spray

An AM process in which a high-velocity jet of solid-phase particles is used to produce a near-net shaped part at temperatures well below the melting point of the powders being applied.

Directed Energy Deposition (DED)

An AM process in which focused thermal energy is used to fuse materials, by melting them, as they are being deposited. There is also Hybrid DED that consists of any combination of DED with computer numerically controlled machining. This method is similar to welding but very detailed. Typical media include wire or powder metal, although ceramics and polymers may also be used.

Material Extrusion

An AM process in which material is selectively dispensed through a nozzle or orifice. Typical media includes thermoplastic or composite filament.

Material Jetting

An AM process in which droplets of the build material are selectively deposited. Typical media include photopolymers or wax.

Powder Bed Fusion (PBF)

An AM process in which thermal energy selectively fuses regions of a powder bed. Typical media include metal powders.

Sheet Lamination

An AM process in which sheets of material are bonded to form an object. Examples include ultrasonic welding to bind metal sheet and adhesive binding of paper.

Vat Photopolymerization

An AM process in which liquid photopolymer in a vat is selectively cured by light activation polymerization.

REQUIREMENTS

TECHNICAL DATA

AM Technical Data Packages (TDP) include, at a minimum, the same level of component definition as traditional TDPs (e.g., blueprint, dimensions and tolerances, material requirements and functional requirements). When the Army owns the design, the TDP must include material property design allowable data as well as material specifications. For components organically manufactured by the Army, the TDP may include manufacturing computer files, manufacturing work instructions and process control documents.

ADVANCED MANUFACTURING PROCEDURES FOR ARMY AVIATION APPLICATIONS

a. Categories of Applications. For Army Aviation applications, AM parts, components, and support products will be managed under the category 0-3 construct detailed in Table 1. Information is required in support of an airworthiness assessment regardless of category. The categories are defined and color coded based on an increasing level of required information to obtain an authorization for their intended use. Categories color coded in green will require little to no developmental work for qualification beyond the qualification requirements for a traditionally manufactured component, and as defined by the appropriate engineering support organization. Categories color coded in yellow require a light to moderate degree of substantiation for qualification. Categories color coded in orange and red require a moderate to heavy degree of substantiation for qualification.

Table 1. Part, Component and Support Product Categorization

Shop Aids and Non-Flyable Prototypes	Components not installed on the aircraft	Category 0
Fixtures, Jigs and Tooling		
Ground Support Equipment		
Flight Parts/Components	Non-critical component (no safety, operation or readiness impact)	Category 1
	Readiness and Operational impact, not safety	Category 2
	Safety impact to include Critical Safety Items	Category 3

b. The categories depicted above will give the Systems Readiness Directorate (SRD) and manufacturers (Army or contracted) the ability to identify the appropriate material allowables required (e.g., C-Basis, D-Basis, S-Basis), based on AMACC paragraph 5.1.1.2. Once the category has been determined and the manufacturer documents the AM process to be utilized to produce the component, the SRD will coordinate with the manufacturer and respective acquisition project office (if applicable) to approve the quality inspection and acceptance plan which demonstrates compliance with the material allowables required. If material allowables are required, then the testing and establishing for those allowables are the responsibility of the proponent of the part, component, or support product. The process to create an allowable database may mirror that for traditional metallic material allowable testing, or for composite material allowable testing, or a combination of both and will be dependent on the component as well as the category and process chosen.

c. Based on the part categorization as well as the technology maturity and stability, Table 2 through 4 lists potential (P = Potential) and required (R = Required) information to be considered for each application category. The items listed are highly dependent on the Failure Mode, Effects, and Criticality Analysis (FMECA) for the particular part, component, or support product. Additionally, requirements may differ between one time and fleet wide authorization of AM items. The SRD will provide a final list of required items for a specific part, component, or support product when it is deemed necessary based on design approach (metal, special factor, composite or point design) and specific usage through an Airworthiness Qualification Plan (AQP). Considerations will include whether the part is a new design, a redesign of a traditionally manufactured part, or a conventional part being repaired using AM techniques.

Table 2. Potential and Required Data Requests Category 1

Application:	**Flight**
Airworthiness Impact:	**None**
	Cat 1
Qualification Item	
Material	
Material Identification	**R**
Material Specification Documentation	**R**
Material Properties/Allowable	**P**
Design	
Design Development Testing	**P**
Form, Fit and Function Check	**R**
Component Specification Documentation	**R**
Safety Margin Analysis (Static, Fatigue, Fracture)	**P**
Validation Test (proof/static load, dynamic)	**P**
Manufacturing	
Process Specification Documentation	**R**
Machine Qualification & Manufacturing Instruction/Plan	**P**
On-Site Manufacturing Process Audit	**P**
Parts Quality	
First Article Verification	**P**
Acceptance Inspection (dimensional, NDI, surface, functional)	**P**
In-situ Test Coupons	**P**
Recurring in Service Inspection	**P**
Overarching Quality Program and Traceability	**R**

Table 3. Potential and Required Data Requests Category 2

Application:	**Flight**
Airworthiness Impact:	**Readiness & Operational**
	Cat 2
Qualification Item	
Material	
Material Identification	**R**
Material Specification Documentation	**R**
Material Properties/Allowables	**R**
Design	
Design Development Testing	**P**
Form, Fit and Function Check	**R**
Component Specification Documentation	**R**
Safety Margin Analysis (Static, Fatigue, Fracture)	**R**
Validation Test (proof/static load, dynamic)	**P**
Manufacturing	
Process Specification Documentation	**R**
Machine Qualification & Manufacturing Instruction/Plan	**R**
On-site Manufacturing Process Audit	**P**
Part Quality	
First Article Verification	**P**
Acceptance Inspection (dimensional, NDI, surface, functional)	**R**
In-situ Test Coupons	**P**
Reoccurring in Service Inspection	**P**
Overarching Quality Program and Traceability	**R**

Table 4. Potential and Required Data Requests Category 3

Application:	**Flight**
Airworthiness Impact:	**Full**
	Cat 3
Qualification Item	
Material	
Material Identification	**R**
Material Specification documentation	**R**
Material Properties/Allowable	**R**
Design	
Design Development Testing	**P**
From, Fit and Function Check	**R**
Component Specification Documentation	**R**
Safety Margin Analysis (Static, Fatigue, Fracture)	**R**
Validation Test (proof/static load, dynamic)	**P**
Manufacturing	
Process Specification documentation	**R**
Machine Qualification & Manufacturing Instruction/Plan	**R**
On-Site Manufacturing Process/Audit	**R**
Part Quality	
First article Verification	**R**
Acceptance inspection (dimensional, NDI, surface, functional)	**R**
In-situ test coupons	**R**
Recurring in Service Inspection	**R**
Overarching Quality Program and Traceability	**R**

APPLICABILITY

This document currently only applies to components that will be installed on aircraft, Categories 1 through 3.

MATERIAL IDENTIFICATION

Material identification positively ensures that the material used for fabrication is the appropriate material for the system design requirements and application, with appropriate controls to ensure the material delivered and used meets specification requirements. For Category 1, a Manufacturer's Tech Data Sheet or equivalent is sufficient. For Category 2 and 3, the material shall be identified via a qualified product list per government/industry/OEM specification.

MATERIAL SPECIFICATION DOCUMENTATION

Material specification is the description of the material, including requirements, tolerances, shelf life, specifications, suppliers and safety data. For Category 1, a Manufacturer's Tech Data Sheet or equivalent is sufficient. For Category 2 and 3, the materials specification shall be published by government, industry, or an OEM.

AMACC section 19.1.4 Material and Process Specifications, provides airworthiness requirements for the development of a material specification.

MATERIAL PROPERTIES/ALLOWABLES

Material properties are determined to an appropriate statistical significance to meet the intent of the material property reliability requirements and structural analysis requirements. For Category 1, a Manufacturer's Tech Data Sheet or equivalent is sufficient. For Category 2 and 3, the statistically derived materials properties must be established as defined.

DESIGN DEVELOPMENT TESTING

The purpose of establishing material characterization and mechanical properties is to support design and analysis of a structurally efficient aircraft design that meets the strength, rigidity, fatigue, damage tolerance, durability, environmental, observability, energy absorption and other requirements of the applicable specifications. Key properties for material selection and design applications include strength, elongation, fracture toughness, damage growth rates, fatigue, stress corrosion, damage initiation thresholds, damage growth thresholds, density, corrosion resistance, population of intrinsic anomalies, surface reflectivity, thermal stability, coefficient of thermal expansion, fire resistance, fluid resistance, and surface roughness. This section describes coupon test requirements required at a minimum to qualify AM materials.

Where applicable, AM tensile and fatigue test coupons should be fabricated for at least three separate “layup” directions:

a. Longitudinal (i.e. X or Z cartesian coordinate direction, where X and Z are in the same plane as each AM layer being incrementally formed),

b. Transverse (i.e. Y cartesian coordinate direction, where Y is orthogonal to each AM layer being incrementally formed), and

c. 45-degree-off-axis (i.e. longitudinal direction of tensile test coupon is 45 degrees off axis from either X, Y or Z cartesian coordinate axis).

The airworthiness substantiation should be provided to ensure design data and allowable material properties is prepared in accordance with the Metallic Materials Properties Development and Standardization (MMPDS) Handbook, sections 5.2.1, 5.2.17, and 6.3 of MIL-STD-3063 and in accordance with the requirements of the Aircraft System Specification, using ADS-13 for guidance. Design development testing should include testing used for substantiation of the design and any repair concepts. Design Data and Allowable Material Properties Report(s) should include: (1) Sources for existing design allowables, test methods used to develop design allowables, processes used to manufacture test coupons, environmental and operational effects on material properties, how statistical methods will be applied to test results to develop the design allowables, effects of impact damage and other barely visible damage, and data and analyses to substantiate compliance with applicable design requirements. (2) The test materials and processes should be those intended for use in production aircraft. The allowables should be traceable to the production parts via material specifications and process specifications or repair or modification procedures.

FORM, FIT AND FUNCTION CHECK

Form, fit and function define the parameters that set the characteristics of a part, with:

a. Form: the shape, size, dimensions, mass, weight and other visual parameters that uniquely distinguish a part.

b. Fit: The ability of a part to physically interface with, connect to, or become an integral part of another part.

c. Function: The action or actions that a part is designed to perform.

The design should be validated by verifying form, fit, and function of an as-built test article.

COMPONENTS SPECIFICATION DOCUMENT

Details the general component requirements to include part or subsystem envelope, interfaces and critical dimensions, performance requirements (loads, temperatures,

thermal expansion, cycles, failure modes), design and analysis requirements (analysis methods, margin of safety, design values/allowables) and manufacturing and inspection requirements.

SAFETY MARGIN ANALYSIS

The purpose of the safety margin analysis is to identify the relative structural performance demands on the part. Parts with high structural margin are less sensitive to variations and uncertainty in material performance. The following aspects should form, at a minimum, the basis of the structural assessment: loads environment, environmental degradation, vibratory/modal response, ultimate strength, yield strength, point strain, high cycle fatigue, low cycle fatigue, and fatigue crack growth rate.

VALIDATION TEST

Validation tests are structural tests either as a non-destructive process control check (workmanship proof, acceptance test) on each unit produced or a destructive test to establish the structural integrity of the part design on one or more individual units (integrity proof, qualification test) and are performed statically and/or dynamically.

PROCESS SPECIFICATION DOCUMENTATION

Process specification establishes process controls for repeatable production of the component. The process specification documentation includes the Process Control Document (PCD) which is established/substantiated by the producer and authorized by Engineering Support Activity (ESA). The PCD may address key process variables, process interruption procedures, build layout, digital file and software configuration control, equipment identification including serial number(s), equipment calibration and maintenance plan and feedstock handling and storage plan. Process specification documentation may also address machine and process approval, statistical process control and training requirements.

MACHINE QUALIFICATION & MANUFACTURING INSTRUCTION/PLAN

The manufacturing plan identifies the proposed nature and sequence of the manufacturing methods, tools, test equipment, material, processes and manpower required to produce the product. The manufacturing plan will be assessed for process repeatability or process certification. Individual machines will be independently qualified unless determined to be unnecessary by SRD. AM components, when qualified, will have machine specific approvals. Machine to machine variability substantiation is required to ensure conforming parts are made over all machines when multiple machines will be used for production.

ON-SITE MANUFACTURING PROCESS AUDIT

This is an audit (prior to part production) where the SRD approves the implementation of the manufacturing plan and process controls. The audit itself may be delegated to the

Defense Contracts Management Agency (DCMA) if approved by SRD on a case-by-case basis. This includes the approval of the fixed/frozen process and its controls.

First Article Verification

"First Article" is a preproduction model, initial Production sample, test sample, first lot, pilot lot, or pilot model used to evaluate and verify, by means of analysis, inspection and test, the conformance with specified requirements before or in the initial stage of production. This ensures that the producer has suppliers, processes, procedures, materials, policies and standards in place that can furnish a conforming product meeting all technical requirements for acceptance. The First Article may be an article chosen from the first production lot instead of a true first piece with SRD approval.

Acceptance Inspection

Acceptance Inspection is a careful and critical examination and/or test of goods prior to government acceptance and issuance for use. Acceptance Inspections may include several methods used to determine acceptability (conforms to requirements) of the product such as, but not limited to, dimensional, finish, material and surface characteristics or certification, non-destructive inspection (NDI) and functional testing. Inspection techniques must be selected to detect flaws inherently produced by the specific AM process and flaw sizes critical to component performance.

In-situ Test Coupons

In-Situ test coupons are printed concurrently with the part. They are used to indirectly test the quality of a printed fabrication process. Test coupons are inspected to ensure proper characteristics are met such as tensile strength, density/porosity, chemistry, material microstructure, etc. The use of coupons for testing is a necessary step in accurately and reliably monitoring fabrication quality and consistency. Drawings and/or Technical Data Packages should define the number of test coupons, their orientations, and specific testing requirements for acceptance. If test coupons are manufactured as part of the component print instead of as separate articles, the technical data should identify the test coupon locations. In-Situ test coupons may be tested in the as-printed or a post-processed condition if the mechanical test results can be shown to be a reliable indicator of the quality of the fully processed part. Post Processed In-Situ test coupons shall be processed concurrently with the part(s).

In-Situ process monitoring data (e.g. input feed material monitoring, thermal imaging, in-line chemical analysis) may be used as additional indicators of component quality. If the fused data can be shown to reliably predict component quality, this fused data can replace in-situ coupon mechanical testing with SRD approval.

CONTINUED AIRWORTHINESS

The vendor should substantiate what inspections/NDI will be needed during the life cycle of the component to ensure the Continued Airworthiness of the asset is achieved. The vendor should also provide justification as to how the design took into consideration the long-term maintainability and repairability of the asset for reparable items.

RECURRING IN SERVICE INSPECTION

Calendar time or flight hour based scheduled inspections are defined in Army technical manuals. For AM components designed to replace existing traditionally manufactured components, any changes needed to technical manuals, Depot Maintenance Work Requirements (DMWR), and other Army publications due to configuration changes to the AM part should be identified.

OVERARCHING QUALITY PROGRAM

Suppliers are certified to an overarching standard for Quality Management systems such as SAE AS9100 that is specific for the aerospace and aviation industry. AS9100 certification is typically required and compliance audited for participating industry manufacturers. For critical safety, critical application and mission critical items used for fleetwide application, the AS9100 standard and traceability requirement within AS9100 should be applied.

REFERENCES

ADS-13 (Air Vehicle Material and Processes)

AMACC (Army Military Airworthiness Certification Criteria).

Metallic Materials Properties Development and Standardization (MMPDS) Handbook

MIL-STD-3063 (Rotorcraft Structural Integrity Program)

SAE AS9100 (Quality Systems, Aerospace, Model for Quality Assurance in Design, Development, Production, Installation and Servicing).