Methodologies for Qualification of Additively Manufactured Aerospace Hardware

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Overview of Discussions

• Additive Manufacturing at NASA
• NASA MSFC AM technical standards
• Key AM Qualification Concepts
• Foundational Controls
  • Qualified Metallurgical Process
  • Material properties
• Part production process
  • Qualified Part Process
• Observations, Challenges, and Closing
NASA is not homogeneous
• Technical and risk cultures vary by facility and mission as shaped by its history
• Human-rated spaceflight
  • JSC, KSC, MSFC
• Space Science
  • GSFC, JPL
• Aeronautics
  • LaRC, GRC, ARC
Additive Manufacturing at NASA

AM in space-related NASA missions:

For-space:

In-space:
Supporting the Mission

**Earth**
- Notional Commercial Platform
- ISS
- Commercial launch Vehicles

**Moon**
- SLS
- Orion
- Robotic Surface Missions
- Lunar Orbital Platform - Gateway
- PPE - Habitat - Airlock - Logistics

**Mars**
- Mars robotic exploration, technology development

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**In LEO**
- Commercial & International partnerships

**In Cislunar Space**
- A return to the moon for long-term exploration

**On Mars**
- Research to inform future crewed missions
Additive Manufacturing (at MSFC)

• Extensive experience in Additive Manufacturing (AM) technologies, and have been involved in about 30 different AM systems in the past 26 years.

• Over $10M capital investments in metallic powder bed systems in the past 5 years, and have committed significant engineering manpower resources

• NASA AM Objectives
  • Decrease production lead time & costs
  • Develop Flight Certification Standards
  • Process development and characterization
  • Share knowledge and data in pursuit of smart vendor base
  • Design optimized components & test at relevant conditions

• Appropriate Application
  • High complexity & difficult to manufacture
  • Low production rate
  • Long lead time & high cost
Motivation: **Laser Powder Bed Fusion** in near term, human-rated flight projects:
- Space Launch System
- Orion Spacecraft
- Commercial Crew Program

Document content is determined by
- **Policy**: MSFC-STD-3716 and
- **Procedure**: MSFC-SPEC-3717
We will return to this concept repeatedly
Overview of Current Requirements

Flowcharts from MSFC-STD-3716
Overview of Current Requirements

Flowcharts from MSFC-STD-3716

First Part of Lecture:
General Requirements and Foundational Process Controls
Overview of Current Requirements

Flowcharts from MSFC-STD-3716

Second Part of Lecture:
Part Production Controls
General Requirements and Foundational Process Controls
Additive Manufacturing Control Plan
- Critical to define implementation policies for program or project
- Describes implementation of all requirements
  - Includes tailoring of requirements
- Becomes governing document in place of standards
Overarching and Foundational Controls

Quality Management System
- Critical to define implementation policy
- Describes implementation of all requirements
- Becomes governing document in place of standards
Equipment and Facility Control Plan

- Plan required by Standard
  - Procedures in Specification
- Flexibility in implementation
- Governs AM equipment and facility
  - Qualification
  - Maintenance
  - Calibration
Personnel Training
- Training Plan required by Standard
  - Expectations in Specification
  - Flexibility in implementation
  - Covers all personnel involved in AM
    - Consistent framework for training and certification of abilities
  - Clear delineations of abilities and responsibilities associated with granted certifications
  - Evaluations demonstrating adequacy
  - QMS awareness
Qualified Metallurgical Process

Begins as a **Candidate** Met. Process

Defines aspects of the basic, **part agnostic**, fixed AM (L-PBF) process:

- Feedstock
- Fusion Process
- Thermal Process

Enabling concept

- Machine qualification and re-qualification
- Process control metrics, SPC
- Design values
Feedstock Controls

- Method of manufacture
- Chemistry
- Particle Size Distribution
- Particle morphology
- Blending and doping controls
- Cleanliness and contamination
- Packaging, labeling, environmental controls
- Reuse controls
Candidate Metallurgical Process

Fusion Controls

• Equipment:
  • Make, Model, Serial Number
  • Software/Firmware versions
  • Settings (dosing, recoater speed)
• Atmosphere Controls
  • Oxygen limits
  • Ventilation flow rate
  • Gas quality (purity, dew point)
• Fusion Parameters
  • Layer thickness
  • Power, speed, hatch, contours...

Source: Fraunhofer IWU
Fusion Controls

Tolerance to variation

- Part build scenarios create variation in process conditions
  - Thermal history effects
  - Scan patterns
- “Process Box” evaluation for qualification
- QMP needs to be “centered” in the process box to allow robust part build capability

Candidate Metallurgical Process

- **Hot**
  - High Energy
  - Keyhole porosity
  - Overheating/burning

- **Cold**
  - Low Energy
  - Lack-of-fusion

Process Limit Boundary:
- Outside boundary = defects

Variation Boundary due to part thermal history:
- Must stay within Process Limit Boundary

Process Box: Resulting variations in nominal commanded process due to part geometry, scan pattern and thermal history
Thermal Process
Post-build Thermal Processing

- Includes definition of all thermal process steps
- **Evolution of microstructure**
- Stress Relief, Hot Isostatic Pressing, Solution Treating, Aging, etc.

IN718 Microstructural Evolution
Qualification the Candidate Metallurgical Process

Establishes a QMP: Qualified Metallurgical Process

**Step 1: Metallurgical Qualification**
- Consistency throughout build area
- Tolerance to variation
- Interface quality (restart, contour passes, striping, islands, multi-laser zones)
- Top layer melt pools
- Microstructural evolution
  - Final state free of strong texture

Melt Pool Evaluation
Qualified Metallurgical Process

Qualification the Candidate Metallurgical Process
Establishes a QMP: Qualified Metallurgical Process

Step 2: Surface texture and detail resolution
- Reference Parts
- Mix of qualitative and quantitative measures
Qualified Metallurgical Process

Qualification the Candidate Metallurgical Process
Establishes a QMP: Qualified Metallurgical Process

Step 3: Mechanical properties
• Tensile, fatigue, toughness...
• Registration through Equivalence
  • Material Property Suite
  • “In-family” performance

QMP “Registration” is the process of demonstrating properties of the qualified process are equivalent to those in the applicable MPS - the next topic.
The Material Property Suite (MPS) consists of four inter-related entities:

1. Data Repository
2. Design Values
3. Process Control Reference Distribution
4. SPC acceptance criteria for witness testing
Material Property Suite

Data Repository
Includes data from
• Qualification testing
• Material Characterization
• Pre-production Article Evaluations

Grouping of data
Group data by
• QMP = Material/process/heat treat
• “Combinable” conditions for design
Data Repository, continued
Contains all data needed for
• Setting Design Values
• Property equivalence evaluations and QMP Registration
• Setting the Process Control Reference Distribution
Material Property Suite

Design Values

- Statistically substantiated
- Applicable sources of variability included
- Utilizes all appropriate data sources in Repository
- May include additional margin for safety
Process Control Reference Distribution

- Statistically describes nominal witness behavior
- Utilizes all appropriate sources of witness coupon data in Repository
- Used to set acceptance criteria for witness tests
Material Property Suite

Statistical Process Control Acceptance Criteria

- Derived from PCRD
- Acceptance criteria for witness tests

SPC Acceptance Criteria for Witness Testing
PCRD and SPC Criteria

- Witness test acceptance is **not** intended to be based upon design values or “specification minimums”
- Acceptance is based on witness tests reflecting properties in the MPS used to develop design values
- Suggested approach
  - Acceptance range on mean value
  - Acceptance range on variability (e.g., standard deviation)
  - Limit on lowest single value
Checkpoint: Key AM Qualification Concepts

- Qualified Metallurgical Process (QMP)
- Statistical Process Control (SPC)
- Material Properties Suite (MPS)
- Qualified Part Process (QPP)

Rationale for Qualified AM parts
Part Production Controls
Overview of Current Requirements

Part Production Controls

Candidate Part

Foundational Process Control Requirements
- Definition of Metallurgical Process
- Qualification of Metallurgical Process
- Equipment Control
- Personnel Training
  - Material Property Suite
  - Material property data
  - Design values
  - Process Control Reference Distribution
  - Statistical Process Control Criteria

Part Production Control Requirements
- Design
  - Part Classification
  - Part Production Plan
  - Pre-Production Article Evaluation
  - Manufacturing Readiness Review
  - Qualified Part Process
  - Production Engineering Controls
  - Production Controls
  - Acceptance testing / Statistical Process Control

Additive Manufacturing Control Plan

General Requirements
- Quality Management System
- AMCP
- General Requirements
- QMS
- MSFC-MP-3707
- "Requirements levied by MSFC-STD-3716

Part Production Controls
- Design Process
- Classify Part
- PPD
- Pre-Prod Article Plan
- Pre-Prod Article Evaluation
- Pre-Prod Article Report
- MIE
- SRR
- Production Engineering Controls
- Production
- NDE Acceptance Test
- Service
- MPS Data
- Design Properties
- SPC Criteria
- FCP
- Qualification Maintenance Calibration
- Machine 1 Master QMP/R
- Machine 2 Master QMP/R
- Machine 3 Master QMP/R
- Machine 4 Master QMP/R
- Machine 5 Master QMP/R
Design Process

• Design For Additive Manufacturing Paradigm Shift
  • New benefits bring new constraints
  • Must decide manufacturing method as early as possible

Self-Supporting Angles

Topology Optimization FDM Tool Rac.

Build Simulation

Powder Removal Features

Hybrid crown & perforated block support
Part Classification

Classification Questions

1. Catastrophic Failure?
2. Heavily Loaded?
3. Does the build have challenging aspects or areas that cannot be inspected?

Classification System:
- Class A1
- Class A2
- Class A3
- Class A4
- Class B1
- Class B2
- Class B3
- Class B4
Part Classification

- Part Classification system is a **risk communication** tool
  - What happens if the part fails?
  - How severe is the stress in the part?
  - How challenging is the part to design, build, and **inspect**?

- Established criteria at each step for consistency

- The higher a part’s classification, the more stringent the downstream requirements become
  - B4 parts should need less scrutiny than an A1 part
  - Non-destructive evaluation needs also likely to differ

- Part-specific tailoring starts with classification
Challenges to the classification system encountered early

- Draft version contained a Class C for non-service components
  - Intent: fit check parts, demonstrations, visual/design aids
  - Revision now considering a “non-structural” for-service Class C
- Did not account for Science Mission Classes (biased to human-rating perspective)
  - Mission classes A-D are defined per NASA NPR 8705.0004
  - Hubble Telescope is a Class A and a Cubesat would be a Class D
- Part Class and Mission Class together influence the requirement set to maintain appropriate levels of mission assurance commensurate with the scenario.
- Future Agency-Level documents will be written for each of the following areas
  - Manned Space Flight
  - Non-Manned Space Flight, with Mission Classes A-D
  - Aeronautics
Part Production Plans force integration of part processing

- Interdependence of layout and downstream requirements
  - Surface finishing
  - Inspection
  - Powder removal

- Common Challenges:
  - Integrated Structural Integrity Rational
  - Required statement of how part integrity is assured (NDE, proof test, process controls)
Part Production Plan

- PPP, Common Challenges (Continued)
  - Locked build files
  - Understanding cryptographic hash
  - Description of controlled post processes
  - NDE Plan
  - Pre-Production Article Plan
    - Critical Areas
    - Thin Sections
    - Thick Sections

Stray vectors
Establishing a **Qualified Part Process**

- Pre-Production Article Evaluation
  - Powder removal, dimensions, surface quality, mechanical properties, internal quality, microstructure, high risk areas...
- Additive Manufacturing Readiness Review
  - Stakeholder review of production engineering record, part drawing, approved PPP, Pre-Production Article Report...
- If successful, **AMRR demarcates when part process is qualified**
  - Complete part manufacturing process is locked for production
    - No changes without re-qualification or proper disposition
  - QPP state is documented in the **Quality Management System**
Key AM Qualification Concepts

Qualified Metallurgical Process (QMP)

Statistical Process Control (SPC)

Qualified Part Process (QPP)

Material Properties Suite (MPS)

Rationale for Qualified AM parts
Part Production — Follow-through on controls

- Statistical Process Control (SPC)
  - Stand Alone acceptance, just making one part
    - A1: 6 tensile, 2 HCF, 2 Met, 1 Chemistry, 1 Full height Contingency
  - Compare to PCRD
- Continuous Production
  - A1: 4 tensile, 1 Met, 1 Chemistry, 1 Full height Contingency
  - Compare to continuous Control Chart
- Intermittent SPC evolution builds during production
- SPC Challenges:
  - Do the samples stay with the parts?
  - How to flag a part without the samples tested?
  - Setting limits that identify drift
Common Challenges

• Turn around of samples used to monitor builds
  • Often three or more months from build to fully heat treated test data
  • Delay is a risk!

• Conventional manufacturing facilities and vendors are not used to the required level of process control
  • Much more difficult when working with vendors
  • Switching Alloys
  • Powder Reuse

• Cleaning of AM parts for contamination-sensitive applications

• Understanding “Influence Factors” in mechanical properties

• Implementing fracture control

• Maintaining the Digital Thread
How to approach in-situ monitoring of AM processes?

• Harnessing the technology is only half the battle
  • Detectors, data stream, data storage, computations
• Second half of the battle is quantifying in-situ process monitoring reliability

Community must realize that passive in-situ monitoring is an NDE technique

1. Understand physical basis for measured phenomena
2. Proven causal correlation from measured phenomena to a well-defined defect state
3. Proven level of reliability for detection of the defective process state
   • False negatives and false positives → understanding and balance is needed

Closed loop in-situ monitoring adds significantly to the reliability challenge

• No longer a NDE technique – may not be non-destructive
• Establishing the reliability of the algorithm used to interact and intervene in the AM process adds considerable complexity over passive systems
• Final Box: Service!

Injector
• Decreased cost by 30%
• Reduced part count: 252 to 6

FTP
• Schedule reduced by 45%
• Reduced part count: 40 to 22
• Successful tests in both Methane and Hydrogen

MCC
• Schedule reduction > 50%
• SLM with GRCop-84
• Methane test successful

GRCop-84 3D printing process developed at NASA and infused into industry

1/25/2018

Ox-Rich Staged Combustion Subscale Main Injector Testing of 3D-Printed Faceplate

LOX/Methane Testing of 3D-Printed Chamber Methane Cooled, tested full power

AM Demonstrator Engine
Currently, there are two primary opportunities to ensure AM reliability

1. In-Process Controls (Control what you do)
   - Qualify the AM Process (QMP) and Part Process (QPP)
   - Understanding fundamentals, and knowing the process failure modes (pFMEA)
   - Identifying observable metrics and witness capabilities
   - Meticulous process scrutiny through SPC

2. Post-Process Evaluation (Evaluate what you get)
   - Non-destructive Evaluation, Proof testing
   - Post-build process monitoring data evidence

Part reliability rationale comes from sum of both in-process and post-process controls, weakness in one must be compensated in the other
Key AM Qualification Concepts

- Qualified Metallurgical Process (QMP)
- Statistical Process Control (SPC)
- Material Properties Suite (MPS)
- Qualified Part Process (QPP)

Rationale for Qualified AM parts
Thank you!
Missions Classes based on risk:
- Class A (per NPR 8705.0004)
- Class B (per NPR 8705.0004)
- Class C (per NPR 8705.0004)
- Class D (per NPR 8705.0004)
- Associated GSE and test hardware

<table>
<thead>
<tr>
<th>Characterization</th>
<th>Class A</th>
<th>Class B</th>
<th>Class C</th>
<th>Class D</th>
</tr>
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<tbody>
<tr>
<td>Priority (Criticality to Agency Strategic Plan)</td>
<td>High priority</td>
<td>High priority</td>
<td>Medium priority</td>
<td>Low priority</td>
</tr>
<tr>
<td>National significance</td>
<td>Very high</td>
<td>High</td>
<td>Medium</td>
<td>Low to medium</td>
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<tr>
<td>Complexity</td>
<td>Very high to high</td>
<td>High to medium</td>
<td>Medium to low</td>
<td>Medium to low</td>
</tr>
<tr>
<td>Mission Lifetime (Primary Baseline Mission)</td>
<td>Long, &gt; 5 years</td>
<td>Medium, 2-5 years</td>
<td>Short, &lt; 2 years</td>
<td>Short, &lt; 2 years</td>
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<tr>
<td>Cost</td>
<td>High</td>
<td>High to medium</td>
<td>Medium to low</td>
<td>Low</td>
</tr>
<tr>
<td>Launch Constraints</td>
<td>Critical</td>
<td>Medium</td>
<td>Few</td>
<td>Few to none</td>
</tr>
<tr>
<td>In-Flight Maintenance</td>
<td>N/A</td>
<td>Not feasible or difficult</td>
<td>Maybe feasible</td>
<td>May be feasible and planned</td>
</tr>
<tr>
<td>Alternative Research Opportunities or Re-flight Opportunities</td>
<td>No alternative or re-flight opportunities</td>
<td>Few or no alternative or re-flight opportunities</td>
<td>Some or few alternative or re-flight opportunities</td>
<td>Significant alternative or re-flight opportunities</td>
</tr>
<tr>
<td>Examples</td>
<td>HST, Cassini, JIMO, JWST</td>
<td>MER, MRO, Discovery payloads, ISS Facility Class Payloads, Attached ISS payloads</td>
<td>ESSP, Explorer Payloads, MIDEQ, ISS complex subrack payloads</td>
<td>SPARTAN, GAS Can, technology demonstrators, simple ISS, express middeck and subrack payloads, SMEX</td>
</tr>
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### APPENDIX A. PART PRODUCTION PLAN CONTENT

This Appendix is not a mandatory part of the standard. The information contained herein is intended for guidance only.

The L-PBF PFP is expected to address the following content. Items in this list that are fully controlled by the ANC P need not be repeated in the PFP. The controlled requirements of the ANC P, part drawing, and PFP are to be sufficient to produce the production engineering record.

- **Drawing number and part name**
- **Part summary, providing a brief summary of**
  - The purpose of the part in context to the system,
  - The operational environments (temperatures, fluids),
  - CAD model views to illustrate the part and key features
- **Material**
  - Identification of the QM P specified for production.
  - Identification of MR P used for assessment
- **Part classification with summary rationale for consequence of failure, structural demand, and AM risk**
- **Integrated Structural Integrity Rationale for the part**
  - Describe limiting factors in strength and fracture analyses
  - Highlight areas of high structural demand and high AM risk per classification
  - Describe all non-destructive testing and the degree of coverage or any limitations
  - Describe all proof test operations, including role in integrity rationale, method of analysis, and coverage or limitations
- **List of required witness tests, witness articles, and associated acceptance requirements**
- **Illustration of the complete build with part orientation, location, and witness specimens**
- **Summary list or table with all production steps in sequence as governed by the Production Engineering Record**
  - Include all key operations such as build, powder removal, as-built inspection, support removal, platform removal, heat treating, cleaning, welding, machining, surface treatments, NDE steps, proof test.
- **Description of any specific controls required for post-build part processing operations that are process-sensitive, i.e., outcomes of the operation is difficult to verify but critical to the part**
- **Pre-production article requirements, or reference to a separate plan**
- **List of references supporting the PFP (analysis reports, fracture control reports, etc.)**
- **Complete list of all required part acceptance certificates of compliance information**
  - Dimensional inspection report, NDE reports, powder lot, build logs, etc.

CHECK THE MASTER LIST VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE