Supplier Issues Related to Additive Manufacturing Certification

Gearing-up Additive Manufacturing for Space Applications

Rick Russell

NASA Technical Fellow for Materials

NASA Engineering and Safety Center

October 26, 2016

Acknowledgement

- The MSFC AM team:
  - Kristin Morgan
  - Doug Wells
  - Brian West
  - Arthur Brown

Central Assumptions

- AM does not require a unique certification approach
- Standardization is needed for consistent evaluation of AM processes and parts

NASA AM - Path to Certification

Current NASA Standards for Manned Space Hardware:

- NASA-STD-6016 – Standard Materials and Processes Requirement for Spacecraft
- NASA-STD-5012 – Strength and Life Assessment Requirements for Liquid-Fueled Space Propulsion System Engines
- NASA-STD-5019 – Fracture Control Requirements for Spaceflight Hardware

- The current version of these NASA Standards utilize both NASA internal and industry standards, none which are specific for Additive Manufacturing
  - AWS D17.1 Fusion Welding for Aerospace Applications
  - SAE AMS 2175 Classification and Inspection of Castings
  - SAE AMS 4985 Ti-6-4 Investment Castings
  - All of these documents call for a conservable collection of "applicable documents"

Additive Manufacturing standards are currently very limited

- Universal challenge – not just NASA
- Standard development being done mainly by ASTM Committee F42 on Additive Manufacturing
- Other standard organizations are also working on AM Standards
  - SAE AMS, AWS etc.

Relationships among AM Standards Development Organizations

AMSC
America Makes & ANSI Additive Manufacturing Standardization Collaborative

coordinates

ASTM
Committee F42 on Additive Manufacturing

SAE / AMS-AM
Additive Manufacturing Committee

AWS
D20 Committee on Additive Manufacturing

(MMPDS, NADCAP, and CMH-17 are also active)

NASA-STD-6016A – soon to be released

4.2.4.11 Additive Manufacturing

Guidelines documents and standards for additive manufacturing are in development at this time. The requirements of this NASA Technical Standard on M&P controls, materials design values, metallic and nonmetallic materials, and nondestructive inspection apply to hardware manufactured by additive techniques, just as they do for traditional manufacturing techniques. For nonstructural, nonmetallic 3-D printed hardware, controlled and verified processes are essential; but other M&P aspects like flammability, toxic offgassing, and vacuum outgassing also apply, just as for any other nonmetallic material.

When structural hardware is manufactured by additive manufacturing techniques, a manufacturing and qualification plan shall be submitted to NASA and approved by the responsible NASA M&P and design organizations.

Key aspects of producing structural metallic hardware by additive manufacturing techniques, such as direct metal laser sintering (DMLS) and selective laser melting (SLM), include proper development of structural design values and controlled processes, although other requirements, such as stress-corrosion resistance and corrosion control, also apply. Verification of appropriate process control should include first article inspection to verify proper material properties and macro/microstructure and mechanical property testing of integrally manufactured specimens from each hardware unit.

NASA needs

- NASA can not wait on America Makes or other national standards organizations to develop AM standards
  - MSFC has taken the lead to develop a standard
- Program partners in manned space flight programs (Commercial Crew, SLS and Orion) are actively developing AM parts
  - Flight as earlier as 2018
  - It has been recommended that the MSFC standard is used as the interim basis for certification via tailoring
- Application to other NASA missions needs to be considered
  - Science missions
  - Aeronautics

MSFC Standard

- Drafted a Center-level MSFC requirement (Jul 2015)
- Conduct wide-reaching Peer Review (Aug – Oct 2015)
  - NASA Centers and NESC
  - Partners (Aerojet Rocketdyne, SpaceX, Lockheed Martin, et al)
  - Industry (GE, Honeywell, et al)
  - Certifying Agencies (FAA, USAF, ONR, et al)
- Revise as needed / levy as required (Dec 2016)
- Watch progress of standards organizations and other certifying Agencies (ongoing)
- Incorporate AM requirements at an appropriate level in Agency specifications (later)

National Aeronautics and Space Administration

MSFC-STD-xxxx
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

This official draft has not been approved and is subject to modification.
DO NOT USE PRIOR TO APPROVAL

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

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED

MSFC Standard - Requirements

- Set of 26 requirements that address
  - Part Classification
  - Metallurgical Process Control
  - Material Property Development
  - Part Process Control
  - Part Inspection and Acceptance
  - Equipment Process Control
  - Vendor Process Control

MSFC Standard - Products

- **QMP** Qualified Metallurgical Process (foundational control)
  - Analogous to a very detailed weld PQR
- **PCRD** Process Control Reference Distribution (foundational control)
  - Defines reference state to assess process consistency
- **DVS** Design Value Suite (properties database)
  - “Allowables,” integrated through PCRDs
- **PDP** Part Development Plans (Overview and implementation)
  - For communication and to convey risk
  - Present part classification and rationale
- **MRR** Manufacturing Readiness Review
- **QPP** Qualified Part Process
  - Finalized “frozen” part process
- **FAI** First Article Inspection
- **ECP** Equipment Control Plans
  - Machine qual, re-qual, maintenance, contamination control
- **QMS** Quality Management System
  - Required at AS9100 level with associated audits

MSFC Standard – Tailoring starts with Classification

- Classification Criteria:

All AM parts are placed into a risk-based classification system to communicate risk and customize requirements

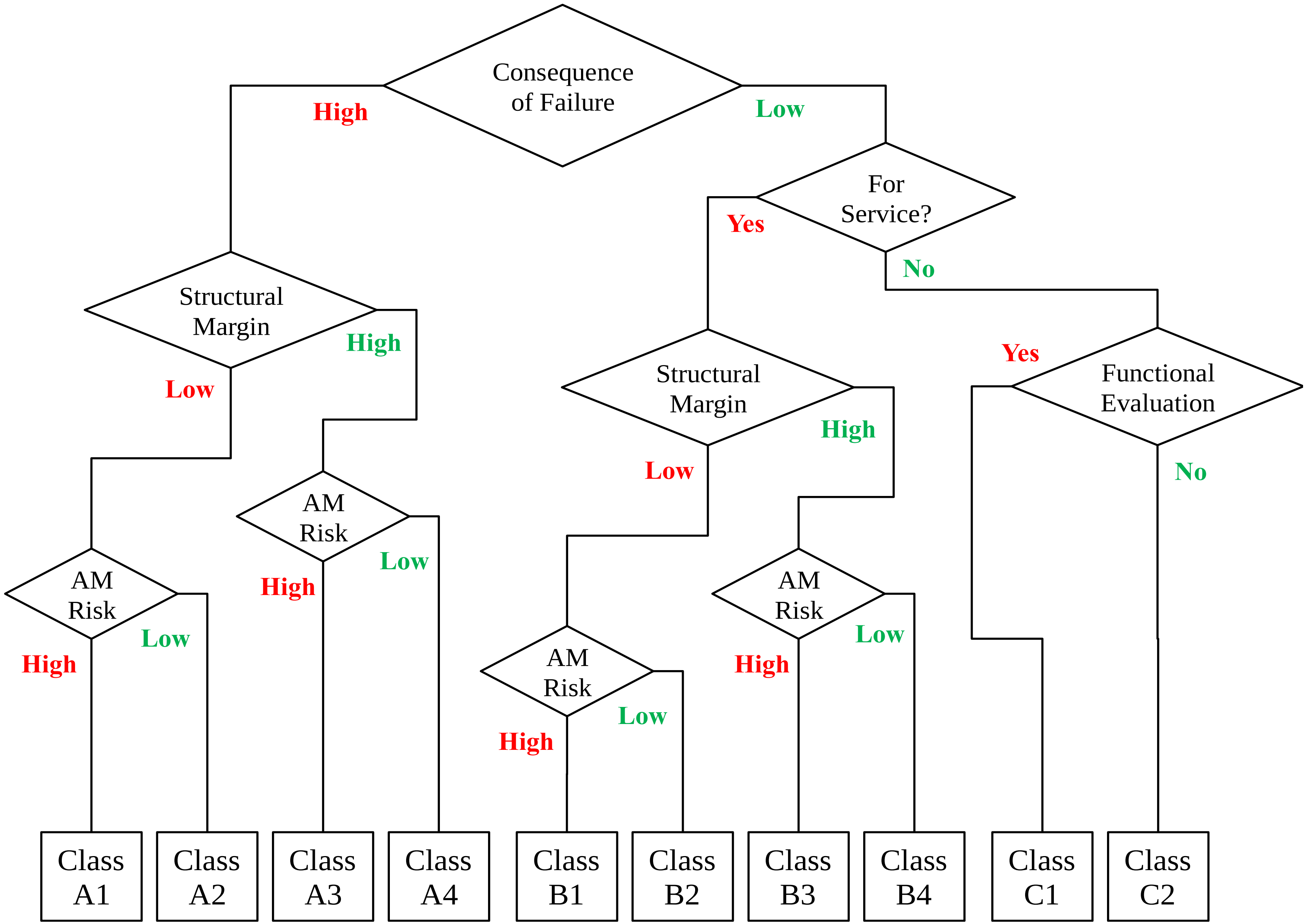
Three decision levels

1. Consequence of failure (High/Low) {Catastrophic or not}
2. Structural Margin (High/Low) {strength, HCF, LCF, fracture}
3. AM Risk (High/Low) {Integrity evaluation, build complexity, inspection access}

Example:

A3 = fracture critical part with low structural demand (high margin) but challenges in inspection, geometry, or build

Classification Tree



AM Structural Margin Criteria

Material Property	Criteria for High Structural Margin
Loads Environment	Well-defined or bounded loads environment
Environmental Degradation	Temperature only
Ultimate Strength	30% margin over factor of safety
Yield Strength	20% margin over factor of safety
Point Strain	Local plastic strain < 0.005
High Cycle Fatigue, Improved Surfaces	4x additional life factor or 20% below required fatigue limit cyclic stress range
High Cycle Fatigue, As-built Surfaces	10x additional life factor or 40% below required fatigue limit cyclic stress range
Low Cycle Fatigue	No predicted cyclic plastic strain
Fracture Mechanics Life	10x additional life factor
Creep Strain	No predicted creep strain

AM Risk Criteria

Additive Manufacturing Risk	Yes	No	Score
All critical surface and volumes **can be reliably inspected**, or the design permits **adequate proof testing** based on stress state?	0	5	
As-built surface **can** be fully removed on all fatigue-critical surfaces?	0	3	
Surfaces interfacing with sacrificial supports **are fully accessible** and improved?	0	3	
Structural walls or protrusions are ≥ 1mm in cross-section?	0	2	
Critical regions of the part **do not** require sacrificial supports?	0	2	
		Total	

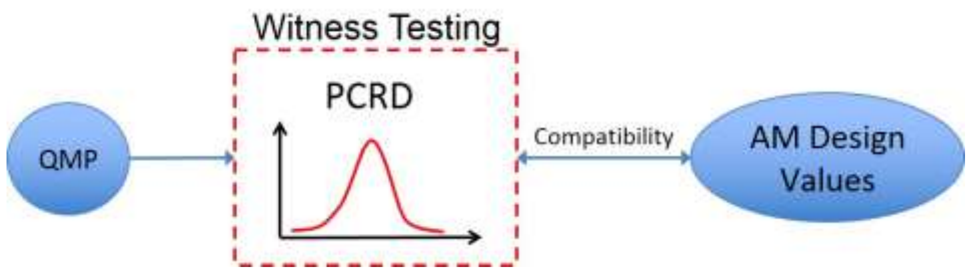
AM risk = HIGH, if cumulative AM Risk score >=5

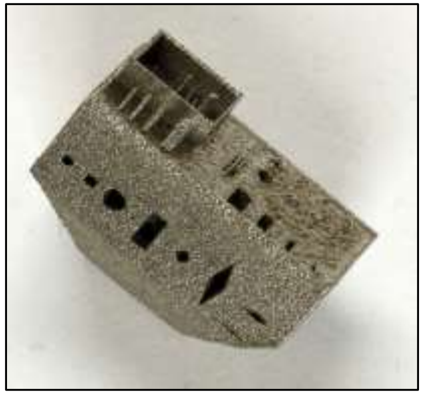
Design Value Suite - DVS

- Collection of material properties developed for a specific AM alloy and condition for use in the structural assessment of the part
- Properties are developed with appropriate statistical significance
  - MMPDS equivalent (meets the intent)
- The DVS shall be developed and maintained for each applicable AM alloy and condition
  - Development process to be submitted to NASA via MUAs
  - Actual values available for review
  - The DVS is only applicable to parts submitted to an appropriate Qualified Part Process (QPP)
- Applicability of the DVS to the part is ensured by thorough First Article Inspection (FAI) and continuous process monitoring of mechanical properties through witness specimens

Qualified Metallurgical Process - QMP

- Analogous to a Weld Procedure Qualification Record (PQR)
- Each PBF machine shall have an alloy-specific QMP
- Required for Class A or B parts
- Powder feedstock controls and recycle limits
- Fusion process specification
- Microstructural evaluation
- Thermal processing
- Customized QMP, when unique process control is required
- QMP mechanical property evaluation
  - Establish mechanical performance baseline
  - Feeds the PCRD
- Process Control Reference Distributions (PCRD)
  - Provides a measure of statistical process monitoring
- Reference Parts
  - Provides a baseline for quality of part rendering by the qualified process
- Registration of QMP to DVS
- QMP record
  - Configuration controlled
  - Must be specified by a Qualified Part Process (QPP)





Reference Part

Process Witnessing

- Witness specimens provide direct evidence of the systemic health of the AM process during the witnessed build
- Witness specimens are only an in-direct indicator of AM part quality through inference.
- Types of AM build witness specimens
  - Metallurgical
  - Tensile (strengths and ductility)
  - Fatigue
  - Low-margin, governing properties (as needed)

Product Development Plan (PDP)

- Product Development Plan (PDP), Companion to the part drawing
  - Summary documenting key outcomes of the design and assessment process
  - Require for all parts of Class A1 thru B4
  - Submitted to NASA via an MUA
  - PDP includes
    - Design information
    - Part integrity rationale
      - NDE
      - Proof Testing
      - Dimensional
    - QMPs used for part production
    - FAI requirements
    - Witness sample requirements/criteria
    - Electronic data records
    - Model integrity control
    - Build execution controls
    - Production Planning Record
    - Sequence of post-build processes
    - As-built part inspection
    - Powder removal
    - Weld qualification
    - Surface treatment control
    - Cleaning
    - Markings
    - Handling, packaging shipping
    - List of required Certification of Compliance Records

- Flight rationale for AM parts is tied directly to process control.
- AM process control requires discipline.
- The PDP enforces planning discipline to the complete process required to produce AM parts.

What the MSFC Standard Delivers

- Certified/Qualified design
  - Supported by part classification
- Certified/Qualified materials
  - Statistical basis
- Certified/Qualified process
  - Process control
  - Material property evaluation
  - Womb to tomb
  - Statistically significant
- Certified/Qualified NDE
  - Statistical basis
  - Tied to Fracture Criticality

Approved Product Development Plan

- Qualified Metallurgical Process (QMP)
- First Article Inspection (FAI)
  - First Article Plan
- Witness Requirements/Criteria
- Build execution policies
- Post-build processing

KEY POINT:

Although the MSFC standard was written specifically for the Powder Bed Fusion process it's principles can be applied to any AM process for the purpose of certification

AM Supply Chain Essentials

- Standards & Requirements
  - What set of standards and requirements are being used?
    - Do these standards and requirement meet yours or your customer’s expectations?
    - Does your supplier understand your requirements?
    - Is a gap assessment necessary?
    - What evidence exist for adherence?
    - What is your auditing strategy

- Process Control
  - Supplier must show evidence of a fixed and repeatable process
  - Process control must be accurately defined
  - What margins are allowable?
  - Definition of checks and balances

AM Supply Chain Essentials

- Critical Elements for supplier audit and/or qualification
  - Appropriate reference and document control
  - Part modeling
  - Build set-up
  - Feed stock control
  - Machine maintenance
  - Post-processing parameters
  - Manufacturing plan
  - Build cycle

Barriers to AM Supplier Quality Assurance

- Lack of standards
  - Creates a lack of consistency
- Lack of knowledge
  - Not all AM suppliers appreciate how process control effects part quality
- Technology gaps
  - AM is a rapidly evolving technology
- Large number of processing variables
  - Lack of appreciation as to the effects of all input variables
- Lack of auditing/qualification standards
  - Imperative to understand which processing parameters need to be monitored

Summary

1. AM does not require a unique certification approach
   - Although, technology advances may offer unique opportunities
2. Standardization is needed to provide a consistent set of products
   - Consistent evaluation of AM implementation and controls
   - Consistent evaluation of risk in AM parts
3. Part Classification is useful to provide rapid insight and communicate risk to a reviewer
4. The Qualified Metallurgical Process provides the foundation for standardization
5. Intelligent witness testing for process control is necessary.
6. In the absence of an enforceable standard it is essential to understand your supplier’s or sub-contractors processes and their understanding of the key elements of the AM process

Concluding Remarks

- It recommended that all NASA manned flight programs use the MSFC standard as the interim basis for certification
  - NESC Technical Bulletin to be released
  - NASA Agency wide standard is needed
    - Most of heavy lifting already done via release of MSFC standard
    - Although the standard is written for metallic parts manufactured via SLM the foundational principles outlined can be tailored for any AM process
      - However, significant development required
    - This recommendation need not be specific to manned space flight applications
      - Part classification can help steer proper tailoring
- NASA has been working primarily with the prime contractors and the supply chain is not ready to produce quality parts for manned space flight without direct NASA involvement and coordination.