Standardization in Additive Manufacturing: Challenges in Structural Integrity Assurance

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Additive Manufacturing
For Reactor Materials and Components
Public Meeting

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• NASA is integrating critical AM parts into human-rated flight systems:
  Space Launch System : : Orion Spacecraft : : Commercial Crew

Ensuring structural integrity is the highest challenge - Quality Assurance and standardization are fundamental to this endeavor.
Summary of Topics

1. Additive Manufacturing Standards Landscape
2. Integration of structural integrity rationale in AM
3. Process qualifications – standardization
4. Material property transferability
5. NDE standardization status in AM
6. Impending, near-term reliance on computed tomography
7. Coming reliance on in-situ monitoring
Standardization in Additive Manufacturing

America Makes/ANSI Additive Manufacturing Standardization Collaborative AMSC
Focused on identifying gaps in AM standardization

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Integration of Structural Integrity

- AM components often require a more integrated approach to substantiate the rationale for structural integrity
  - Not a new concept--basics of fracture control--AM atypically complex
  - Developing a structural integrity rationale from multiple mitigations to guard against multiple risks is new to many.
  - Fracture control challenges are more frequent

**MSFC-STD-3716: Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals**

- AM *Part Production Plan* required to illuminate risks
- Includes the *Integrated Structural Integrity Rationale* – a concise summary of how structural integrity is assured commensurate with the part’s risk classification
Integrated Structural Integrity Rationale

**Mitigations**

- Process Controls
  - Process Qualifications
  - In-Situ Process Monitoring
- Process Witness Testing
- **NDE: CT, RT, PT, ET, UT**
- Part Acceptance Tests (dimensional, proof, leak)
- PPA assessment

**Risks**

- Process Escapes
- Physical defects (cracks, voids)
- Material capability debits
- High structural demand
- Complex geometry
- Surface quality
- Uninspectable volume and surface
Process Qualification

Standardization Need: Definition of a Qualified AM Process

Most fundamental of mitigations to ensure structural integrity


- Defines a Qualified Metallurgical Process (QMP) (represents a first attempt)
- Consensus Standards are beginning to establish definitions and requirements

A Qualified AM Process is critical to knowing

- Consistency of process over time and across platforms,
  - Individual machine capability
- What material condition is characterized/represented in design data
- What material condition is expected in parts
- Transferability and equivalence in material structural performance

IN718 Microstructural Evolution
Need consensus definitions of AM process quality for consistency

- Powder controls
- Process parameters
- Chamber environment
- Material integrity / acceptable defect state
- Microstructure evolution
- Mechanical properties
- Surface quality and detail resolution
- Variability across build volume
- Variability with part/bed thermal history

The first question to ask relative to any data, parts, or products from AM:

**How was the AM process qualified?**

Coming hurdle: Accommodating adaptive AM processes

- Move from qualifying process to qualifying algorithm
- Increased reliance on pre-production article evaluations
Material Property Transferability

**Standardization Need:** Establishing Material Property Transferability

- Evaluation of standard specimens for mechanical properties in tensile, fatigue fracture mechanics developed by AM processes
  - **Standard specimens will be used to establish engineering design values**
- How do properties vary within AM parts?
- Essential to association of process qualification to part qualification
- Critical to know properties within part are represented by characterization

**Critical aspects in structural integrity**

- Witness specimen correlation
- “Influence factors” in AM materials
  - Thermal history in build
  - Surface texture
  - Thin section capability
- Capability and reliability of post-processing to homogenize and control microstructural evolution to lessen transferability risk.

ASTM F42.01 Work Item WK49229: Orientation and Location Dependence Mechanical Properties for Metal Additive Manufacturing
NDE Standardization in AM

Standardization Need: Non-destructive Evaluation for AM

E07.10 Work Item – WK47031: *Standard Guide for Nondestructive Testing of Metal Additively Manufactured Aerospace Parts After Build*

F42.01 Work Item – WK56649: *Standard Practice/Guide for Intentionally Seeding Replica into Additively Manufactured (AM) Structures*

High Priority: *Defect Catalog for AM*

- Analogous to references used to identify defects in casting or welding
- Correlation of defect type to AM process, NDE method, and reliability of detection
- Correlation of defect risk to structural integrity

**Vertical Lack-of-Fusion**

**Layer, “Multi-site” damage**

**Horizontal Lack-of-Fusion**

**Zero-volume Lack-of-Fusion after HIP**
Near-term Reliance on CT

**Standardization Need:** Computed Tomography (CT) with Quantified Reliability

For aerospace, CT is not an industry standard technique with quantified reliability for detection of defects – Probability of Detection (POD)

Current state of the art: reliance on Representative Quality Indicators (RQIs)

- See ASTM E1817 *Standard Practice for Controlling Quality of Radiological Examination by Using Representative Quality Indicators (RQIs)*

**AM Complications for CT:**
- Penetration vs resolution
- Complex AM geometry
- Low-volume defects
- Physics: beam hardening, edge artifacts, etc.
- Makes generalization difficult

**Planned work in E07.01 Radiography**
- Build on 2D CT and DR standards
- Application to structural integrity requirements such as POD methods may require broader cooperative efforts

**Numerical CT simulations may help with defining detection capability and uncertainty quantification.**
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 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
Additive Manufacturing Qualification Process

- Process sensitivity
- Process data
- Component application

Acceptable SLM Process Operating “Window”

Sensor Data
Acceptance Criteria
Developed Around Operating “Window”

Analysis Methodology for Predicting Functional Performance Variation

Integrated Quality Assurance Approach
Example of development: In-Situ Monitoring

Pore Area and Flaw Type versus SLM Parameters

Flaw types clearly defined and correlated with pore area gradient.

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Example of development: In-Situ Monitoring

- Unique part signatures are generated for DOE processing condition and identified as discernably different than the nominal response
- Methodology to establish control limits around the nominal part signature

Unique Signatures Generated and Discernable For Each DOE Processing Condition

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Final Summary

1. Additive Manufacturing Standards Landscape
   - Diverse and developing rapidly, still limited in detail for structural integrity challenges

2. Integration of structural integrity rationale in AM
   - Essential to understanding risks on a part-by-part basis

3. Process qualifications – standardization
   - AM process qualification needs standard definition

4. Material property transferability
   - Applicability of design values depends upon methods to understand property transferability from coupon to part

5. NDE standardization status in AM
   - Primary, quantifiable reference for structural integrity. Active work items in E07

6. Near-term reliance on computed tomography
   - Needs methodologies to quantify reliability, particularly for low-volume defects

7. Coming reliance on in-situ monitoring
   - Potential great enabler for structural integrity, but caution required.
Thank You

Additive Manufacturing at MSFC