National Aeronautics and Space Administration
Marshall Space Flight Center

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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Structural Integrity in Additive Manufacturing

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

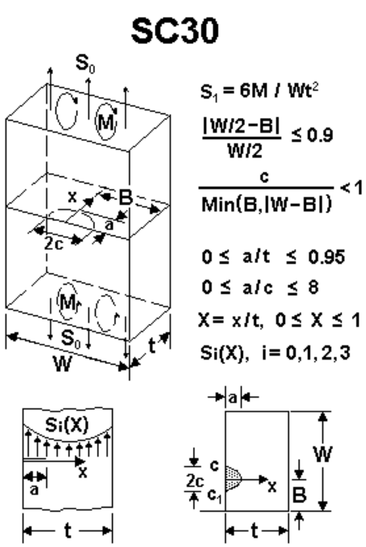
Aerojet Rocketdyne RS-25

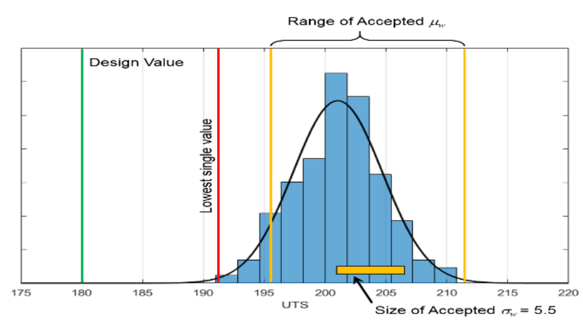
SpaceX SuperDraco

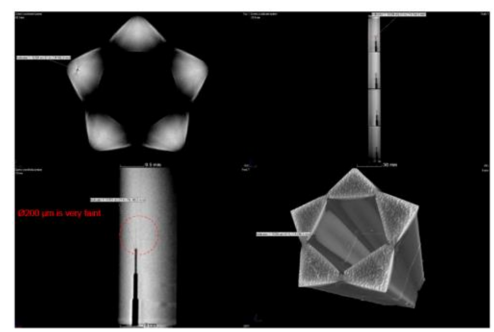
Ensuring structural integrity is the highest challenge - Quality Assurance and standardization are fundamental to this endeavor.

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

America Makes

ANSI American National Standards Institute

- ASTM International
- International Organization For Standardization (ISO)
- American Society of Mechanical Engineers (ASME – Setting the Standard)
- SAE International
- American Welding Society (AWS)
- Institute of Electrical and Electronics Engineers (IEEE Standards Association)
- MITA – Medical Imaging & Technology Alliance, a division of NEMA
- Association for the Advancement of Medical Instrumentation (AAMI – Advancing Safety in Healthcare Technology)
- IPC - Association Connecting Electronics Industries
- Metal Powder Industries Federation (MPIF)

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)

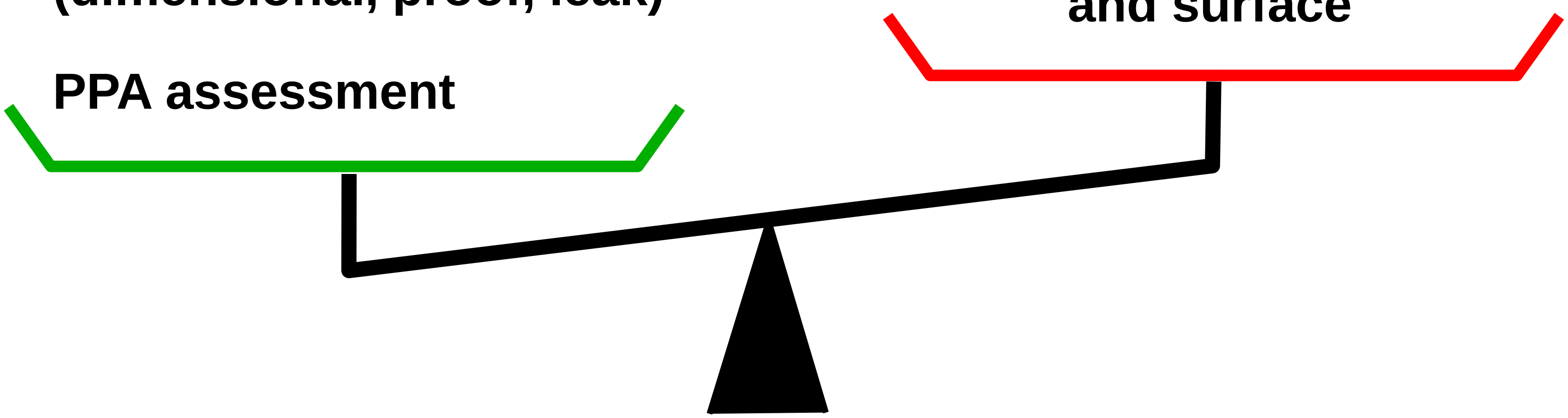
Material capability debits

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

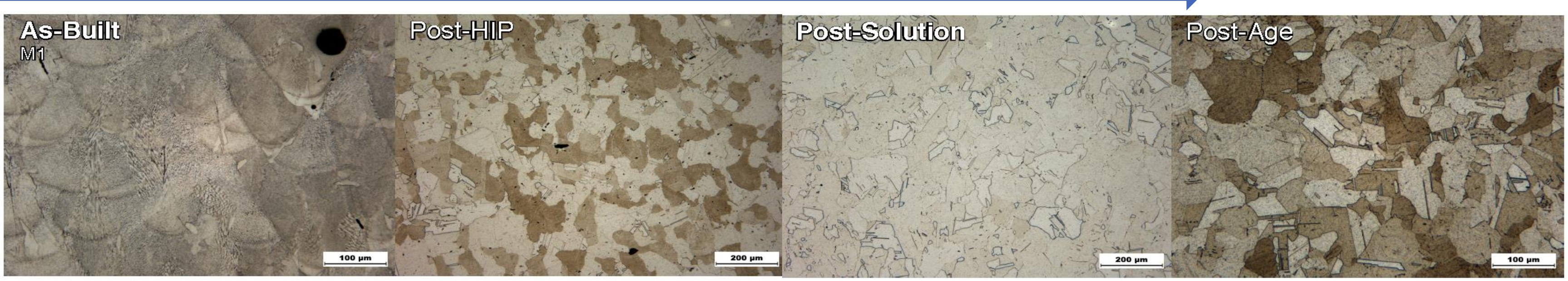
MSFC-SPEC-3717: *Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes*

- 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

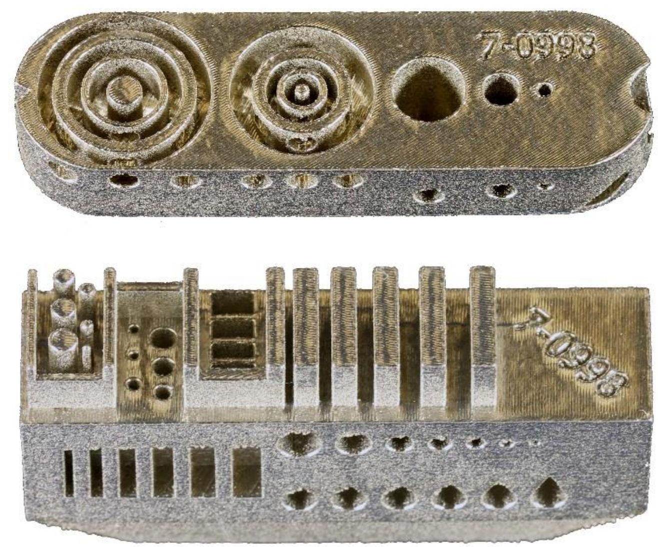


Defining a Qualified AM Process

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

Contour Integrity Reference Part



Build Quality Reference Part

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

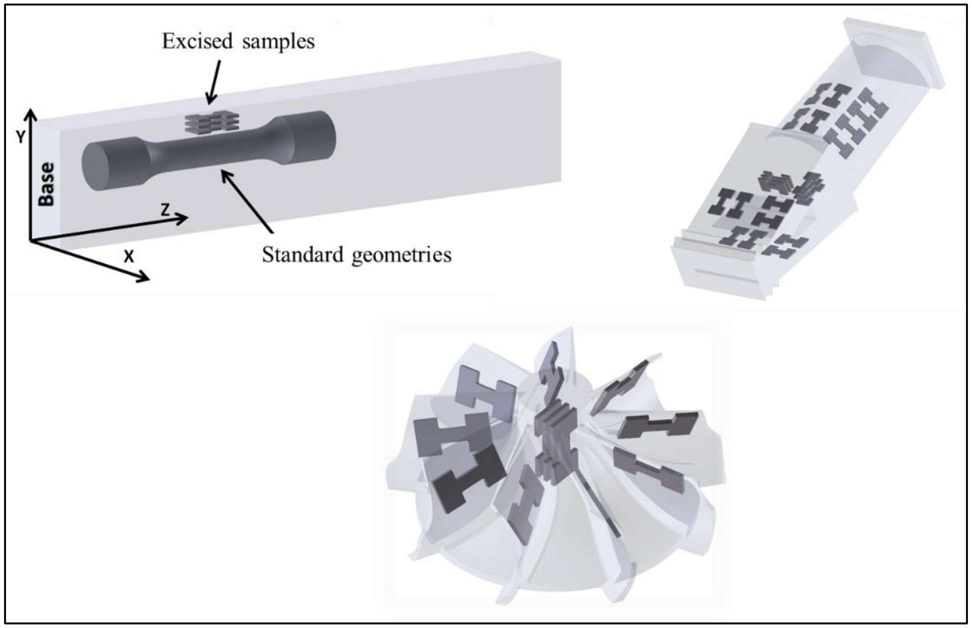
Material Property Transferability

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

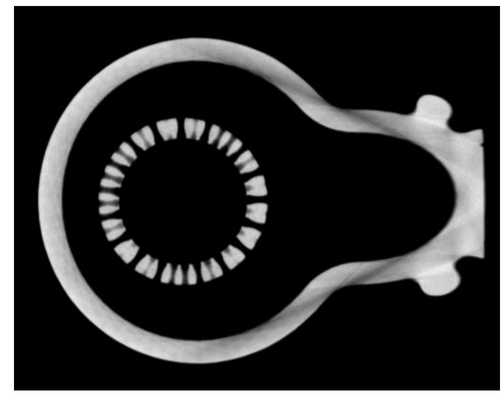
Standardization Need: Non-destructive Evaluation for AM

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

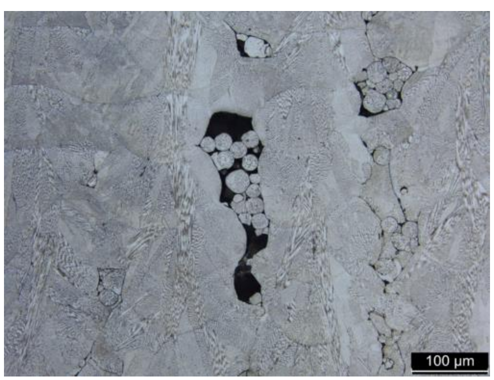
F42.01 Work Item – WK56649: *Standard Practice/Guide for Intentionally Seeding Replica into Additively Manufactured (AM) Structures*

High Priority: *Defect Catalog for AM*

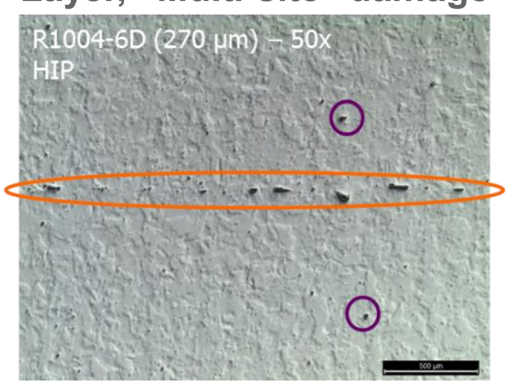
- Analogous to references used to identify defects in casting or welding
- Correlation of defect type to AM process, NDE method, and reliability of detection
- Correlation of defect risk to structural integrity



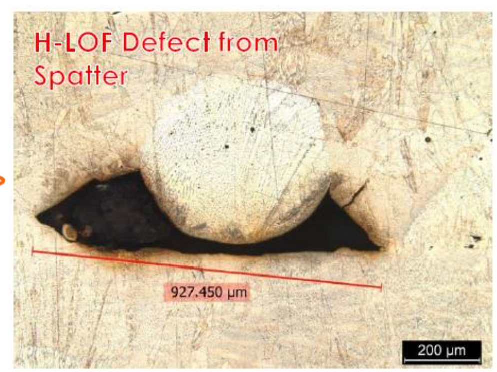
Vertical Lack-of-Fusion



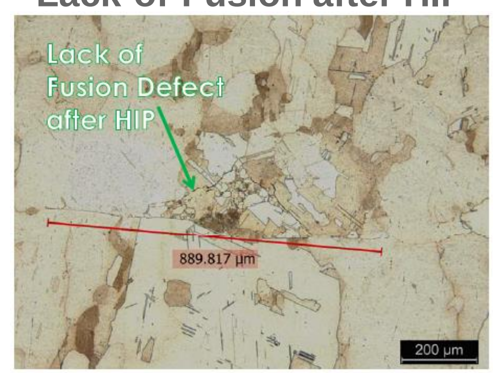
Layer, "Multi-site" damage



Horizontal Lack-of-Fusion



Zero-volume Lack-of-Fusion after HIP



Near-term Reliance on CT

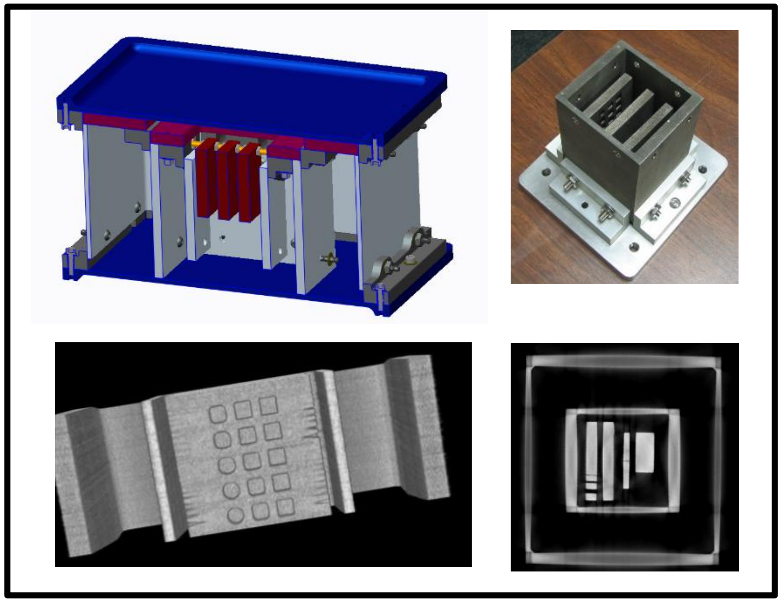
Standardization Need: Computed Tomography (CT) with Quantified Reliability

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)*

MSFC Modular CT Reference Standard



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.

Coming Reliance on In-Situ Monitoring

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

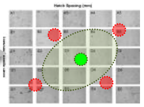
Closed loop in-situ monitoring adds significantly to the reliability challenge

- 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

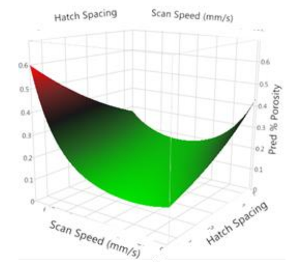
Example of development: In-Situ Monitoring

Additive Manufacturing Qualification Process

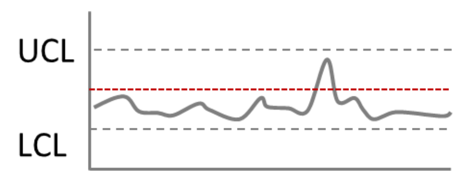
Statistical Analysis and Integration



Process Sensitivity → *Acceptable SLM Process Operating "Window"*

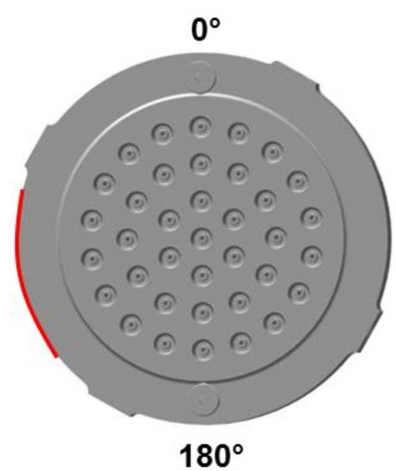


Process Data → *Sensor Data Acceptance Criteria Developed Around Operating "Window"*

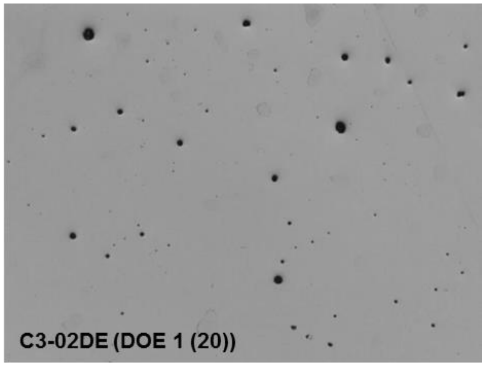


Component Application → *Analysis Methodology for Predicting Functional Performance Variation*

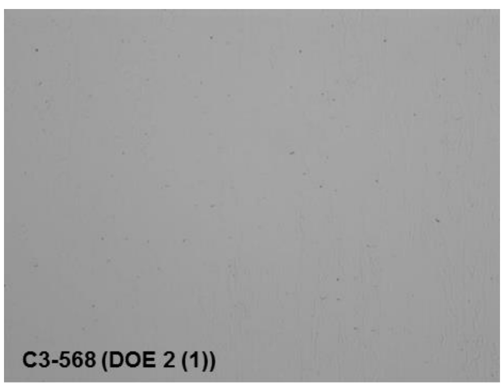
Integrated Quality Assurance Approach



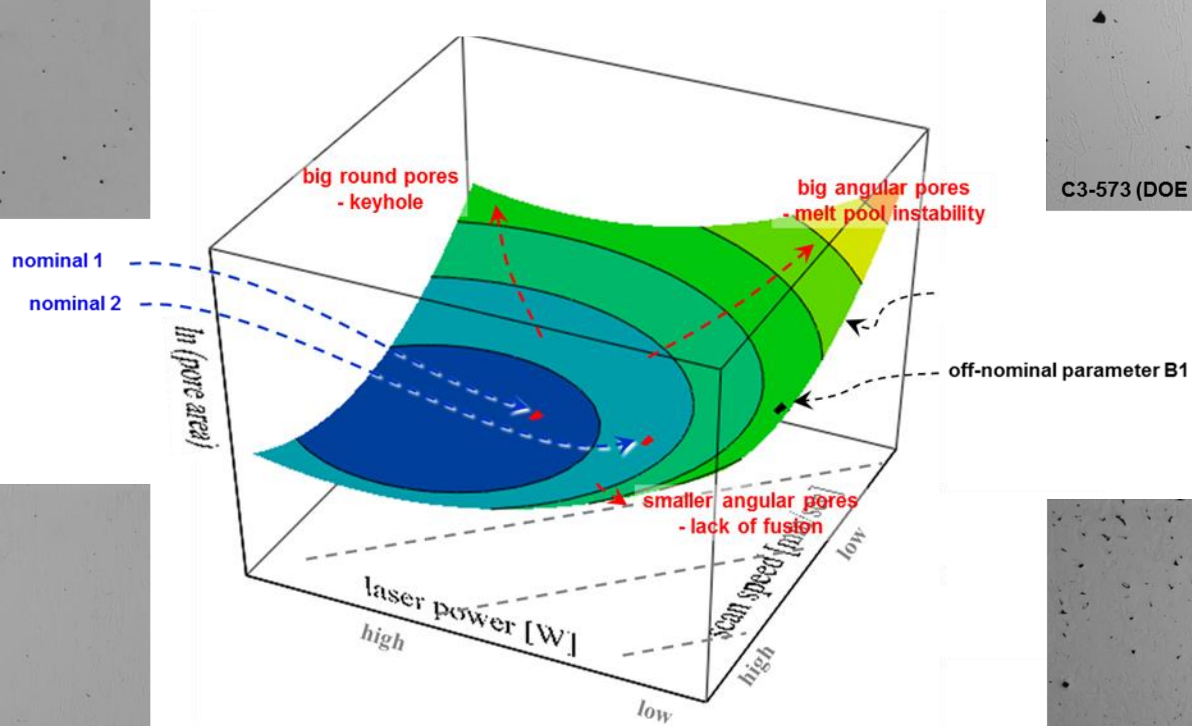
Example of development: In-Situ Monitoring

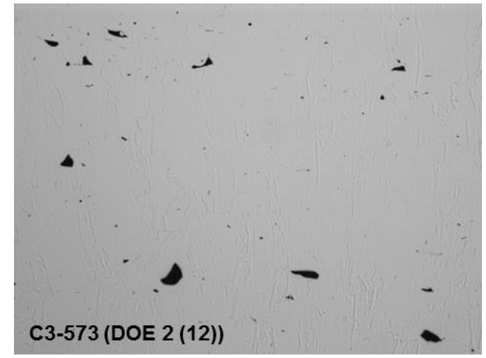

C3-02DE (DOE 1 (20))

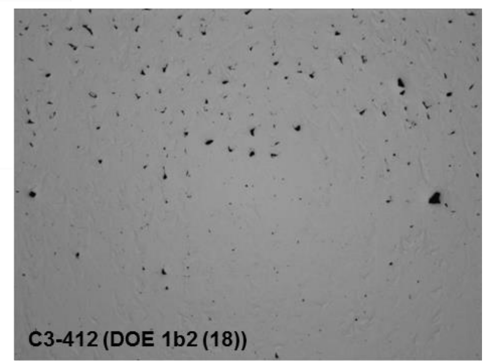
(vertical sections through samples, 50X, as polished)


C3-568 (DOE 2 (1))

Pore Area and Flaw Type versus SLM Parameters



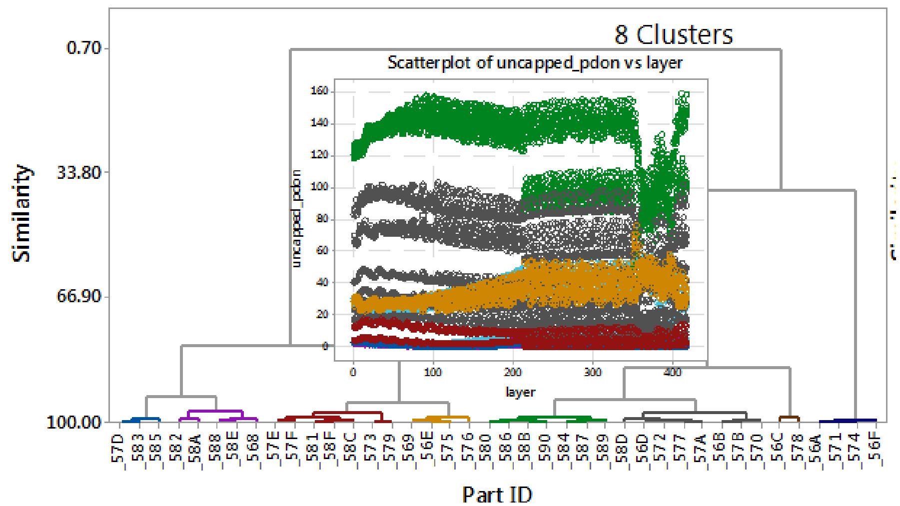

C3-573 (DOE 2 (12))


C3-412 (DOE 1b2 (18))

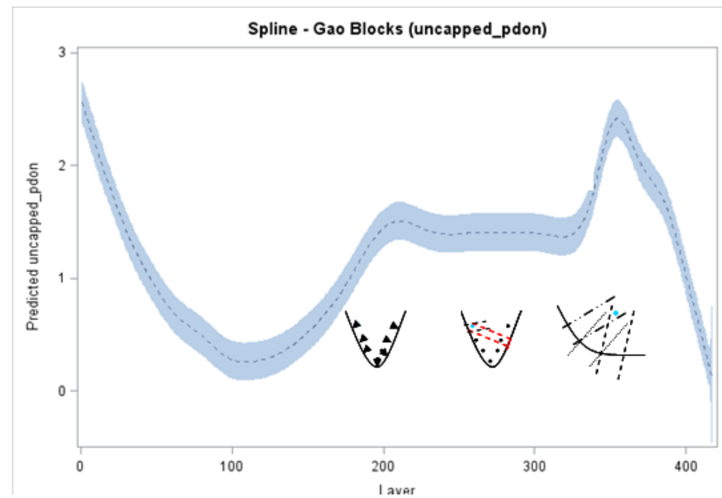
Flaw types clearly defined and correlated with pore area gradient.

Example of development: In-Situ Monitoring

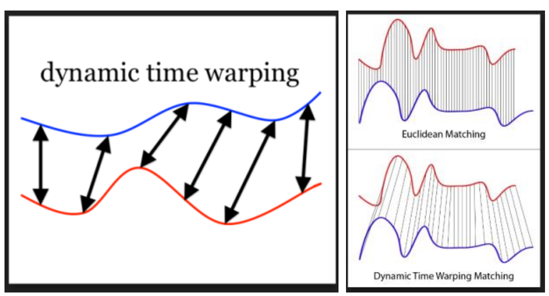
Unique Off-Nominal Signatures



Process Limit Approach Developed



Cluster Analysis Methodology



- 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

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