Additive Manufactured Product Integrity

Jess Waller • NASA WSTF
Doug Wells • NASA MSFC
Steve James • Aerojet Rocketdyne
Charles Nichols • NASA WSTF

Quality Leadership Forum
March 15 & 16, 2017
Cape Canaveral, FL

1:30 - 2:00 PM, Wednesday, March 15, 2017
• NASA is providing leadership in an international effort linking government and industry resources to speed adoption of NDT of additive manufactured (AM) parts to meet the industry needs

• Participants include government agencies (NASA, USAF, NIST, FAA), industry (commercial aerospace, NDE manufacturers, AM equipment manufacturers), standards organizations and academia

• NASA is also partnering with its international space exploration organizations such as ESA and JAXA

• NDT is identified as a universal need for all aspects of additive manufacturing
Key Documents to Improve Safety and Reliability of AM Parts using NDE

NASA Additive Manufacturing Roadmap and NDE-related Technology Gaps
Contacts: Jess Waller (WSTF); James Walker (MSFC); Eric Burke (LaRC); Ken Hodges (MAF); Brad Parker (GSFC)

- NASA Agency additive manufacturing efforts were catalogued
- Industry, government and academia were asked to share their NDE experience in additive manufacturing
- NIST and USAF additive manufacturing roadmaps were surveyed and a technology gap analysis performed
- NDE state-of-the-art was documented
Inconel Pogo-Z baffle for RS-25 engine for SLS

Prototype titanium to niobium gradient rocket nozzle

Aerojet Rocketdyne RL-10 engine thrust chamber assembly and injector

Dynetics/Aerojet Rocketdyne F-1B gas generator injector

28-element Inconel 625 fuel injector

SpaceX SuperDraco combustion chamber for Dragon V2
Additive Manufacturing Technology Gap Analysis
NDE of AM Technology Gaps

- Develop **in-situ monitoring** to improve feedback control, maximize part quality and consistency, and obtain ready-for-use certified parts.
- Develop and refine **NDE** of as-built and post-processed AM parts.
- Develop **voluntary consensus standards** for NDE of AM parts.
- Develop better **physics-based process models** using and corroborated by NDE.
- Use NDE to understand scatter in **design allowables database** generation activities (process-structure-property correlation).
- Fabricate AM **physical reference samples** to demonstrate NDE capability for specific defect types.
- Apply NDE to understand effect-of-defect, and establish acceptance limits for specific defect types and defect sizes.
- Develop **NDE-based qualification and certification protocols** for flight hardware (screen out critical defects).
Key development areas, challenges and promising work captured
• NESC NDE TDT briefed on 10/26/17
Identify Relevant AM Defects
NDE of AM Technology Gaps

- Develop/generate an AM defects catalogue
- Develop **in-process NDE** to improve feedback control, maximize part quality and consistency, and obtain ready-for-use certified parts
- Develop **post-process NDE** of finished parts
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Background

While certain AM flaws (e.g., voids and porosity) can be characterized using existing standards for welded or cast parts, other AM flaws (layer, cross layer, unconsolidated and trapped powder) are unique to AM and new NDE methods are needed.


Note: DED = Directed Energy Deposition, PBF = Powder Bed Fusion
Typical PBF Defects of Interest

Also have unconsolidated powder, lack of geometrical accuracy/steps in the part, reduced mechanical properties, inclusions, gas porosity, voids, and poor or rough surface finish.
Typical PBF and DED Defects

Also interested in (gas) porosity and voids due to structural implications

Note: proposed new definitions in ISO/ASTM 52900 Terminology:

- **lack of fusion (LOF)** — flaws caused by incomplete melting and cohesion between the deposited metal and previously deposited metal.

- **gas porosity**, $n$ — flaws formed during processing or subsequent post-processing that remain in the metal after it has cooled. Gas porosity occurs because most metals have dissolved gas in the melt which comes out of solution upon cooling to form empty pockets in the solidified material. Gas porosity on the surface can interfere with or preclude certain NDT methods, while porosity inside the part reduces strength in its vicinity. Like voids, gas porosity causes a part to be less than fully dense.

- **voids**, $n$ — flaws created during the build process that are empty or filled with partially or wholly un-sintered or un-fused powder or wire creating pockets. Voids are distinct from gas porosity, and are the result of lack of fusion and skipped layers parallel or perpendicular to the build direction. Voids occurring at a sufficient quantity, size and distribution inside a part can reduce its strength in their vicinity. Voids are also distinct from intentionally added open cells that reduce weight. Like gas porosity, voids cause a part to be less than fully dense.
Develop and Capture Best NDE Practice
Round Robin Test Goals

- Develop **in-situ monitoring** to improve feedback control, maximize part quality and consistency, and obtain ready-for-use certified parts.
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Effect of Design Complexity on NDE

Contact: Evgueni Todorov (EWI)

- Great initial handling of NDE of AM parts
- Report has a ranking system based on geometric complexity of AM parts to direct NDE efforts
- Early results on NDE application to AM are documented
- Approach for future work based on CT and PCRT
Effect of AM Part Complexity on NDE

Most NDE techniques can be used for Complexity Groups § 1 (Simple Tools and Components) and 2 (Optimized Standard Parts), some for Group 3 (Embedded Features); only Process Compensated Resonance Testing and Computed Tomography can be used for Groups 4 (Design-to-Constraint Parts) and 5 (Free-Form Lattice Structures):

## Background

NDE options for design-to-constraint parts and lattice structures: LT, PCRT and CT/μCT

<table>
<thead>
<tr>
<th>NDE Technique</th>
<th>Geometry Complexity Group</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>VT</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>LT</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>PT</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>
| PCRT          | Y   | Y | Y   | Y  | Y  | Screenin;
|               |     |   |     |    |    | size   |
|               |     |   |     |    |    | restrictions (e.g., compressor blades) |
| EIT           | Y   | Y | NA  | NA | NA | Screening; size restrictions |
| ACPD          | Y   | Y | P(c) | NA | NA | Isolated microstructure and or stresses |
| ET            | Y   | Y | P(c) | NA | NA |
| AEC           | Y   | Y | P(c) | NA | NA |
| PAUT          | Y   | Y | P(b) | NA | NA |
| UT            | Y   | Y | P(b) | NA | NA |
| RT            | Y   | Y | P(d) | NA | NA |
| X-Ray CT      | Y   | Y | Y   | Y  | NA |
| X-ray Micro CT| Y   | Y | Y   | Y  | Y  |

Key:
- Y = Yes, technique applicable
- P = Possible to apply technique given correct conditions
- NA = Technique Not applicable

Notes:
- (a) Only surfaces providing good access for application and cleaning
- (b) Areas where shadowing of acoustic beam is not an issue
- (c) External surfaces and internal surfaces where access through conduits or guides can be provided
- (d) Areas where large number of exposures/shots are not required

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μCT Requirements

<table>
<thead>
<tr>
<th>225 kV μCT</th>
<th>600 kV MacroCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube</td>
<td>FXE 225.99 microfocus</td>
</tr>
<tr>
<td></td>
<td>Comet MXR 601/HP11 Minifocus</td>
</tr>
<tr>
<td>Focal spot</td>
<td>Approx. 10 μm variable</td>
</tr>
<tr>
<td></td>
<td>0.5 mm fixed (ASTM)</td>
</tr>
<tr>
<td>Detector</td>
<td>PerkinElmer XRD 1620 AN</td>
</tr>
<tr>
<td></td>
<td>PerkinElmer XRD 1621 EN</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>200 μm</td>
</tr>
<tr>
<td></td>
<td>200 μm</td>
</tr>
<tr>
<td>Prefilter</td>
<td>2.5 mm copper</td>
</tr>
<tr>
<td></td>
<td>6-7 mm copper</td>
</tr>
<tr>
<td>Type</td>
<td>Helical CT</td>
</tr>
<tr>
<td></td>
<td>Standard CT</td>
</tr>
<tr>
<td>Proj.</td>
<td>1200 Proj/rot.</td>
</tr>
<tr>
<td></td>
<td>1600 Proj.</td>
</tr>
</tbody>
</table>

Also utilize NASA capability at GRC, KSC and GSFC
PCRT also can distinguish processing effects, for example, SLM samples made with different laser scanning speeds (Ti6-4 Gong/Univ. of Louisville samples)
Nonlinear Resonant Ultrasonic Testing (RUS)

TRL4 system available with advanced software

- Frequency scan at more than more amplitude
- Shows promise for detection of initial defects before catastrophic failure
- Signal not affected by part size or geometry
- MSFC to supply samples to LANL
Coordinated by S. James (Aerojet Rocketdyne)

Electron Beam Freeform Fabrication (EBF$^3$)

NASA LaRC
Inconel 625 on copper

Ti-6Al-4V (4)

SS 316

Al 2216

Laser-PBF (L-PBF)

Gong
Ti-6Al-4V bars

Airbus
Al-Si-10Mg dog bones

Concept Laser Inconel 718 inserts (6) w/ different processing history

Concept Laser Inconel 718 prisms for CT capability demonstration

Characterized to date by various NDE techniques (CT, RT, PT, PCRT, UT)

Electron Beam-PBF (E-PBF)

Met-L-Check
SS 316 PT/RT panels
Characterized to date by various NDE techniques (CT, RT, PT, PCRT, UT, etc.)

**HEX Samples**
Inconel 718
in two different build orientations

**SLM (L-PBF)**
Inconel 625 PT sheets

**Laser-PBF (L-PBF)**
NASA MSFC nominal and off-nominal metal parts (K. Morgan)

**Directed Energy Deposition (DED)**
NASA MSFC ABS plastic parts with and without defects (N. Werkheiser)

**DRDC Porosity Standards**
4140 steel. 0-10% porosity

1.9% porosity

5.1% porosity

Coordinated by S. James (Aerojet Rocketdyne) and J. Waller (NASA WSTF)
Round Robin Sample Activity – illustrative presentations
Working drafts and minutes of webmeetings discussing the standard Guide for NDE of AM aerospace parts are posted on-line:
CT/MET, MSFC/James Walker
*metal SLM parts, MSFC/Kristin Morgan
*ABS plastic parts, MSFC/Niki Werkheiser
CT, GSFC/Justin Jones
*EBF3 metal parts, LaRC/Karen Taminger
POD/fracture critical AM parts, ESA/Gerben Sinnema
AE, MRI/Ed Ginzel
CT/acoustic microscopy, Honeywell/Surendra Singh
UT/PT, Aerospace Rocketdyne/Steve James
CT/RT, USAF/John Brausch, Ken LaCivita
CT, Fraunhofer/Christian Kretzer
CT, GE Sensing GmbH/Thomas Mayer
PCRT, Vibrant Corporation/Eric Biedermann
PT, Met-L-Check/Mike White
Nonlinear RUS, LANL/Marcel Remillieux
*Concept Laser/Marie Ebert
†*Airbus/Amy Glover
†*UTC/John Middendorf, Wright State University/Greg Loughnane
†*CalRAM/Shane Collins

* delivered or committed to deliver samples
† E8 compliant sacrificial dogbone samples
Voluntary Consensus Standards
Gap Analysis
NDE of AM Technology Gaps

- Develop/generate an AM defects catalogue
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Defect type & part complexity determine NDE selection
Process method determines defects determines NDE
Collaboration on **WK47031**

New Standard Nondestructive Testing of Additive Manufactured Metal Parts Used in Aerospace Applications

Created: Target Date: 2018-10-01  Technical Contact: Jeena Walker

**Task Group Members**

- Learn More

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65 current members

NASA, JAXA, ESA, NIST, USAF, GE Aviation, Aerojet Rocketdyne, Lockheed, Honeywell, Boeing, Aerospace Corp, ULA, academia and various AM and NDE community participants are represented

(48 current members as of June ASTM E07 Committee on NDT meeting)
ANSI-America Makes National Collaborative Effort: Proposed New AM Standards
America Makes & ANSI AMSC Findings

- 181 members (early June)
- Walker, Wells, Luna and Waller among NASA-affiliated members on roster
- Industry Review of Roadmap - December 14, 2016
- Comments being reviewed now by appropriate WGs
- The roadmap will be published by the end of February 2017
- 89 standards gaps identified
  - 6 nondestructive evaluation gaps
  - 15 qualification and certification gaps
  - 6 precursor materials gaps
  - 17 process control gaps
  - 5 post-processing gaps
  - 5 finished materials gaps
  - 26 design gaps
  - 8 maintenance gaps
- Future meetings of Standards Development Organizations will discuss how the standards are divvied up
America Makes and ANSI Launch Additive Manufacturing Standardization Collaborative; Kick-off Meeting held March 31, 2016

5 Working Groups established to cover AM standards areas

- Non-Destructive Evaluation (NDE) WG
  Meets: Every other Friday 11 am – 12:30 pm Eastern, beginning May 27, 2016
  Co-chairs: Patrick Howard, General Electric, and Steve James, Aerojet Rocketdyne
  Scope: NDE of Finished Parts
  (NDE for process monitoring under Process Control SG of Process and Materials WG)
  Test methods or best practice guides for NDE of AM parts
  Dimensional metrology of internal features
  Geometry and surface texture measurement techniques (especially for internal features)
  Data fusion of above
  Common defects catalog found in AM parts, and process capability assessments of NDE techniques (e.g., PBF vs. DED defects)
  Terminology (e.g., definition of AM defects)
  Intentionally seeding AM flaws
  Test samples for process capability or NDE technique performance evaluation

- Quality & Certification (Q&C) WG
  Meets: Every other Monday, 2:30 – 4 pm Eastern, beginning May 9, 2016
  Co-chairs: Capt. Armen Kurdian, U.S. Navy, and Shawn Moynan, NIST
  Ensure that all stages of a particular AM process have a set of commonly understood standards to enable qualification (qualification is defined as ensuring suitability to meet functional requirements in a repeatable manner)
  Generate checklists to address all aspects of AM, to cover variability, repeatability, suitability, etc.
  Address all aspects of the AM environment (materials, design, personnel, systems, end product, etc.)
  Identify aspects of AM process which would lend themselves to certification
5 Working Groups established to cover AM standards areas

- Precursor Materials SG
  - Meets: Every other Tuesday, 1-2 pm Eastern, beginning May 3, 2016
  - Leader: Jim Adams, MPIF; Justin Whiting, NIST

- Chemistry
- Cleanliness
- Feed stock
- Characterization
- Safety & Training
- OEM process & control

- Process Control SG
  - Meets: Every other Thursday, 1-2 pm Eastern, beginning May 5, 2016
  - Leader: Justin Whiting, NIST

- Digital format (CAD, CAM, machine software)
- Machine calibration / preventative maintenance
- Machine qualification
- Machine re-start after maintenance
- Operator training
- Parameter control
- Powder handling / blending / use
- Powder flow monitoring
- Powder reuse/recycle
- Safety
- Cybersecurity
- Process monitoring (thermal control, positional control)

- Post-Processing SG
  - Meets: Every other Tuesday, 1-2 pm Eastern, beginning May 10, 2016
  - Leader: Patrick Ryan, LS Management

- Heat Treat
- HIP
- Surface finishing
- Machining
- Removal of Support Material

- Process and Materials WG*
  - Meets: Every 4th Tuesday, 11 am – 12 noon Eastern, beginning June 28, 2016
  - Co-chairs: Todd Rockstroh, GE Aviation, and Art Kracke, AAK Consulting LLC
  - * All members are asked to join one of the 4 Subgroups (SG)

- Future State: Left to Right Enabling Commercialized AM products

- Finished Material
  - Properties SG
    - Meets: Every other Thursday, 1-2 pm Eastern, beginning May 12, 2016
    - Leader: Roger Narayan, North Carolina State University, and Mohsen Seifi, Case Western Reserve University

- Mechanical properties
- Quality control
- Component testing
- Component certification
- Bio-compatibility
- Chemistry
- Design allowables
- Cleanliness
- Microstructure
America Makes & ANSI AMSC Working Groups

• 5 Working Groups established to cover AM standards areas (cont.)

Design WG
Meets: Every other Tuesday, 10-11:30 am Eastern, beginning May 10, 2016
Co-chairs: John Schmelzle, NAVAIR, and Jayanthi Parthasarathy, MedCAD

Input (Design guides, Design intent)
Designing parts (Design tools, Simulation and modeling, Design for assemblies, Design for printed electronics, Design for bio)
Design documentation (Neutral build file, Product definition data sets)
Validation (of design and models)

Maintenance WG
Meets: Every other Monday 2-3:30 pm Eastern, beginning May 16, 2016
Co-chairs: David Coyle, NAVSUP WSS, and Michele Hanna, Lockheed Martin

Scope: Maintenance of parts and machines
Standard repair procedures for parts and tooling
Standard inspection processes
Model based inspection
Standards for tracking maintenance operations
Workforce development
Cybersecurity
Gaps Identified by NDE Working Group

**Standards in progress**

- **E07 - WK47031**: Standard for the Application of NDE to Components Produced by AM Processes
- **F42 - WK56649**: Standard for the identification of Additive Manufactured Flaws detectable by NDE methods

- No Published Standards exist for the design or manufacture of representative flaws from AM processes To be use as NDE Calibration Standards or Phantoms

1. Standard Guide for the Application of NDE to Components Produced by AM Processes
2. Standard for the identification of Additive Manufactured Flaws detectable by NDE methods
3. No Published Standards exist for the design or manufacture of representative flaws from AM processes To be use as NDE Calibration Standards or Phantoms
4. Standard for the fabrication of physical calibration artifacts or phantoms (produced by either subtractive and/or additive processes)
5. Standard for the dimensional measurement of internal features of AM objects
Current and future NDE of AM standards under development (ASTM)

- Balloting begun (CT, MET, PCRT, PT, RT, TT, and UT)
- Motion to register as a formal work item approved by E07.10 (IR, LUT, VIS)
- Future, phys ref stds to demonstrate NDE capability

**E07**
- POC: J. Waller
- Standard Guide for Nondestructive Testing of As-Built and Post-Processed Metal Additive Manufactured Parts Used in Aerospace Applications

**F42**
- POC: S. Singh
- Standard Guide for Intentionally Seeding Flaws in Additively Manufactured Parts

**E07**
- POC: TBD
- Standard Practice for In-situ Monitoring During the Build of Metal Additive Manufactured Parts Used in Aerospace Applications

**E07**
- POC: TBD
- Standard Practice for Dimensional Metrology of Surface and Internal Features in Additively Manufactured Parts

**E07?**
- POC: TBD
- Standard Practice for the Design and Manufacture of Artifacts or Phantoms Appropriate for Demonstrating NDE Capability in Additively Manufactured Parts
- New Guide for *In-situ Monitoring of Additively Manufactured Parts used in Aerospace Applications* (POC: Surendra Singh/Honeywell)

- 1/23/17: E07.10 motion to register a new standard and assign jurisdiction passed
Demonstrate NDE Capability
NDE of AM Technology Gaps

• Develop/generate an AM defects catalogue (NEW)
• Develop **in-process NDE** to improve feedback control, maximize part quality and consistency, and obtain ready-for-use certified parts
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# Actual and Planned NASA Physical Reference Samples for Additive Manufacturing

## Demonstrate NDE capability

<table>
<thead>
<tr>
<th></th>
<th>MSFC-GRC</th>
<th>GSFC</th>
<th>LaRC</th>
<th>JSC-LaRC</th>
<th>KSC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AM process method</strong></td>
<td><em>DMLS</em></td>
<td>DMLS (metal), LS (plastic)</td>
<td><em>LS</em></td>
<td><em>EBF³</em></td>
<td><em>EBM</em></td>
</tr>
<tr>
<td><strong>alloys</strong></td>
<td>titanium, Inconel, and aluminum</td>
<td>titanium, SS PH1, vero-white RGD835</td>
<td><em>SS</em></td>
<td><em>titanium</em></td>
<td><em>titanium</em></td>
</tr>
<tr>
<td><strong>reference standard geometries</strong></td>
<td><img src="image.png" alt="Image" /></td>
<td><img src="image.png" alt="Image" /></td>
<td><img src="image.png" alt="Image" /></td>
<td><img src="image.png" alt="Image" /></td>
<td><img src="image.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>features interrogated</strong></td>
<td>complex geometries; large/thick/dense and very thin cross sections; (universal NDE standard, slabs, rods, gage blocks)</td>
<td>rectangular prisms, rows of cylinders, cylinders, flat-bottom holes, cone</td>
<td>steps, flat bottom holes</td>
<td>bead arrays, steps, holes</td>
<td>2nd iteration (AM): 36 printed in-holes beginning at surface; 9 printed in-spheres internal to the part; cold plate (future)</td>
</tr>
<tr>
<td><strong>AM defects interrogated</strong></td>
<td>porosity/unfused mats, (restart, skipped layers), cracks, FOD, geometric irregularities</td>
<td>hole roughness and flatness/centricity</td>
<td>porosity, lack of fusion</td>
<td>grain structure, natural flaws, residual stress, microstructure variation with EBF³ build parameters</td>
<td>internal unfused sections</td>
</tr>
<tr>
<td><strong>NDE method(s) targeted</strong></td>
<td>post-process 2 MeV and µCT; PT, RT, UT, ET</td>
<td>post-process 2 MeV CT</td>
<td>post-process 2 MeV CT</td>
<td>post-process UT, PAUT</td>
<td>in-process NDE, not UT</td>
</tr>
<tr>
<td><strong>Comments</strong></td>
<td>collaboration with MSFC AM Manufacturing Group &amp; Liquid Engines Office</td>
<td>flat IQI not suitable due to 3D CT artifacts</td>
<td>x-ray CT LS step wedge</td>
<td>Transmit-Receive Longitudinal (TRL) dual matrix arrays</td>
<td>collaboration with CSIRO</td>
</tr>
</tbody>
</table>
Understand Effect-of-Defect
NDE of AM Technology Gaps

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Approach

Determine effect-of-defect on sacrificial specimens w/ seeded flaws

1. Airbus Laser PBF samples
   Investigate effect post-processing on microstructure and surface finish on fatigue properties
   
   Airbus study on effect of process parameters on final properties
   
   Other NDE planned in ASTM NDT Taskgroup

2. UTC Laser PBF samples
   Ti-6Al-4V ASTM E8 compliant dogbones for in situ OM/IR and post-process profilometry, CT and PCRT

Sacrificial Effect-of-Defect Samples
Parallel effort
Determine effect-of-defect on sacrificial specimens w/ seeded flaws

America Makes Ed Morris (VP) call to fabricate samples for NDE in support of ASTM WK47031 effort

3. CalRAM Electron Beam PBF samples
December 18, 2016

TO: Members of Committees E08, E07 and F42

**SAVE THE DATE**

**Round Table Discussion: Mechanical Behavior of Additive Manufactured Components**
May 5, 2016
San Antonio, TX

**About the Event**
A Round Table Discussion on Mechanical Behavior of Additive Manufactured Components will be held Thursday, May 5, 2016 and is sponsored by ASTM Committee E08 on Fatigue and Fracture in conjunction with F42 on Additive Manufacturing Technologies and E07 on Nondestructive. The discussion will be held at the Grand Hyatt San Antonio in San Antonio, TX, in conjunction with the May standards development meetings of the committee.

The Round Table Discussion is a supplement to the Workshop on Mechanical Behavior of Additive Components and will provide a forum for the exchange of ideas regarding the mechanical behavior of components fabricated using additive manufacturing, with a focus on the development of fatigue related standards for additive manufacturing.

For more information please visit: [http://www.astm.org/E08RTD5-2016](http://www.astm.org/E08RTD5-2016)

If you have any questions, please contact me by reply.

Hannah Sparks
Administrative Assistant, Symposia Operations

ASTM INTERNATIONAL
Helping our world work better

100 Barr Harbor Drive, PO Box C700
West Conshohocken, PA 19428-2959, USA
tel +1.610.832.9677

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**Address:**
- Fracture & fatigue of AM parts
- AM parts used in fracture critical applications
- Critical flaw size for AM defects
Qualify & Certify AM Spaceflight Hardware
NDE of AM Technology Gaps

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Background

Qualification & Certification/NASA MSFC Guidance

Background

Comprehensive draft technical standard is in review

All Class A and B parts are expected to receive comprehensive NDE for surface and volumetric defects within the limitations of technique and part geometry

Not clear that defect sizes from NASA-STD-5009§ are applicable to AM hardware

NDE procedural details are still emerging


Contact: Doug Wells (MSFC)

§NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components
Draft NASA MSFC Standard implements four fundamental aspects of process control for AM:

- Metallurgical Process Control
- Part Process Control
- Equipment Process Control
- Build Vendor Process Control

Each aspect of process control has an essential role in the qualification of AM processes and parts and certification of the systems in which they operate. The standard provides a consistent framework for these controls and provides a consistent set of review/audit products.
Overview of MSFC AM Standard

Design for AM: Part Development Plan [PDP]

Part Classification
- Process Definition
- Integrity Rationale

Integrity Assessment NDE/Proof/PC

Build Trials > Dev Articles > First Article

Design Value Suite [DVS]

- Qualified Metallurgical Process [QMP]
  - Feedstock
  - Fusion Process
  - Internal quality*
  - Surface/Detail Rendering*
  - Thermal Processing
  - Mechanical Properties*
    - acceptance metrics

Validation [MRR]

Registered

Process Control Reference Distributions [PCRD]

Qualified Part Process [QPP]

Production

Process Control Witness Evaluations
- Mechanical
- Macro

Quality Management System [QMS]  Equipment Control Plan [ECP]
PDP = Part Development Plans (Overview and implementation)
  • Communication, convey risk
  • Classification and rationale

DVS = Design Value Suite (properties database)
  • “Allowables,” integrated through PCRDs

QMP = Qualified Metallurgical Process (foundational control)
  • Analogous to a very detailed weld PQR

PCRD = Process Control Reference Distribution
  • Defined reference state to judge process consistency

FAI = First Article Inspection

MRR = Manufacturing Readiness Review

QPP = Qualified Part Process
  • Finalized “frozen” part process

ECP = Equipment Control Plans
  • Machine qual, re-qual, maintenance, contamination control

QMS = Quality Management System
  • Required at AS9100 level with associated audits
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}

Part classification is highly informative to part risk, fracture control evaluations, and integrity rationale

**Example:**
A3 = fracture critical part with low structural demand (high margin) but challenges in inspection, geometry, or build
Comprehensive NDE required for surface and volumetric defects

§ NASA classifications should not to be confused with those used in the ASTM International standards for AM parts, such as F3055 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion. The ASTM classes are used to represent part processing only and are unrelated.
THIS IS ONLY THE BEGINNING
Gaps Identified by AMSC NDE Working Group:

- Led by Patrick Howard, GE Aviation
- 28 members drawn from aerospace, automotive and medical industries
- Mapping started May 2016 – September 2016
  - One Face-to-face meeting
- Met bi-weekly – Web meeting
  - Hosted by ANSI
  - 6 to 8 members participated
  - Identified 6 Standardization Gaps
Demonstrate NDE capability

Reference: ASTM E 1320 “Standard Reference Radiographs for Titanium Castings”
<table>
<thead>
<tr>
<th>Additive Manufacturing Risk</th>
<th>Yes</th>
<th>No</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>All critical surface and volumes <strong>can be reliably inspected</strong>, or the design permits <strong>adequate proof testing</strong> based on stress state?</td>
<td>0</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>As-built surface <strong>can</strong> be fully removed on all fatigue-critical surfaces?</td>
<td>0</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Surfaces interfacing with sacrificial supports <strong>are fully accessible</strong> and improved?</td>
<td>0</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Structural walls or protrusions are $\geq 1\text{mm}$ in cross-section?</td>
<td>0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Critical regions of the part <strong>do not</strong> require sacrificial supports?</td>
<td>0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• It is incumbent upon the structural assessment community to define critical initial flaw sizes (CIFS) for the AM part to define the objectives of the NDE.
• Knowledge of the CIFS for AM parts will allow the NDE and fracture control communities to evaluate risks and make recommendations regarding the acceptability of risk.
• CIFS defects shall be detected at the accepted probability of detection (POD), e.g., 90/95, for fracture critical applications.
• Demonstration of adequate part life starting from NASA-STD-5009 flaw sizes is generally inappropriate for fracture critical, damage tolerant AM parts.
• It is recognized that parts with high AM Risk may have regions inaccessible to NDE. To understand these risks it is important to identify the inaccessible region along with the CIFS.
• Parts with low AM risk should exhibit much greater coverage for reliable NDE.
• Multiple NDE techniques may be required to achieve full coverage.
• Surface inspection techniques (PT, ECT, UT) may require the as-built surface to be improved to render a successful inspection, depending upon the defect sizes of interest and the S/N ratio.
• For PT, surfaces improved using machining, for example, require etching prior to inspection to remove smeared metal.
  • Removal of the as-built AM surface to a level of visually smooth may be insufficient to reduce the NDE noise floor due to near-surface porosity and boundary artifacts.
• NDE demonstration parts with simulated CIFS defects are used to demonstrate NDE detection capability.
• NDE standard defect classes for welds and castings welding or casting defect quality standards will generally not be applicable
• Relevant AM process defect types used must be considered.
• AM processes tend to prohibit volumetric defects with significant height in the build (Z) direction. The **concern instead is for planar defects**, such as aligned or chained porosity or even laminar cracks, that form along the build plane. The implications of this are:
  − planar defects are well suited for growth
  − planar defects generally have low contained volume
  − the orientation of defects of concern must known before inspection, especially when detection sensitivity depends on the defect orientation relative to the inspection direction
  − the Z-height of planar defects can be demanding on incremental step inspection methods such as CT
• **Until an AM defects catalog and associated NDE detection limits for AM defects are established, NDE acceptance criteria shall be for part-specific point designs.**
### Structural Margin Criteria

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Criteria for High Structural Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loads Environment</td>
<td>Well defined or bounded loads environment</td>
</tr>
<tr>
<td>Environmental Degradation</td>
<td>Only due to temperature</td>
</tr>
<tr>
<td>Ultimate Strength</td>
<td>30% margin over factor of safety</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>20% margin over factor of safety</td>
</tr>
<tr>
<td>Point Strain</td>
<td>Local plastic strain &lt; 0.005</td>
</tr>
<tr>
<td>High Cycle Fatigue, Improved Surfaces</td>
<td>4x additional life factor or 20% below required fatigue limit cyclic stress range</td>
</tr>
<tr>
<td>High Cycle Fatigue, As-built Surfaces</td>
<td>10x additional life factor or 40% below required fatigue limit cyclic stress range</td>
</tr>
<tr>
<td>Low Cycle Fatigue</td>
<td>No predicted cyclic plastic strain</td>
</tr>
<tr>
<td>Fracture Mechanics Life</td>
<td>10x additional life factor</td>
</tr>
<tr>
<td>Creep Strain</td>
<td>No predicted creep strain</td>
</tr>
</tbody>
</table>
• Draft NASA MSFC Standard identifies AM as a unique material product form and requires the metallurgical process to be qualified on every individual AM machine.

• Developed from internal process specifications with likely incorporation of forthcoming industry standards.
QMP:

- Feedstock control or specification
- AM machine parameters, configuration, environment
- As-built densification, microstructure, and defect state
- Control of surface finish and detail rendering
- Thermal process for controlled microstructural evolution
- Mechanical behavior reference data
  - Strength, ductility, fatigue performance

Diagram:
- Powder Feedstock Controls
- Fusion Process
- Build Process Metrics
- Thermal Process
- Mechanical Properties
- QMP
- Registration

- Method of manufacture
- Chemistry
- Particle size distribution
- Contamination
- Consolidation
- Microstructure
- Defect State
- Surface Finish
- Detail Resolution
- Pattern Plate**
- Reference Part**
- Stress relief
- HIP
- Heat treatment
- Microstructural Evolution**
- Process Control Reference Distribution**
- Design Value Suite registration properties
- Review/Approval of metallurgical process
- QMP Record*
- Document DVS compatibility*

*Quality management system record
**Acceptance criteria metric
Qualified Metallurgical Process (QMP)

- As-built densification, microstructure, and defect state
- Thermal process for controlled microstructural evolution
Qualified Metallurgical Process (QMP)

- Reference Parts
- Control of surface finish and detail rendering
- Critical for consistent fatigue performance if as-built surfaces remain in part

Reference parts:
Metrics for surface texture quality and detail rendering
Overhanging, vertical and horizontal surface texture, acuity of feature size and shape
Qualification & Certification/Qualified Metallurgical Process

• Mechanical behavior reference data
  – Strength, ductility, fatigue performance
  – Process Control Reference Distributions (PCRD)

• Establish and document estimates of mean value and variation associated with mechanical performance of the AM process per the QMP
  – May evolve with lot variability, etc.

• Utilize knowledge of process performance to establish meaningful witness test acceptance criteria
Types of AM build witness specimens

- Metallurgical
- Tensile (strengths and ductility)
- Fatigue
- Low-margin, governing properties (as needed)

What is witnessed?

- Witness specimens provide direct evidence only for 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.
Mechanical Property Witness Procedures

- Move away from spot testing for acceptance against 99/95 design values or specification minimums
- Evaluate with sufficient tests to determine if the AM build is within family
- Compromise with reasonable engineering assurance

Proposed
- Six tensile
- Two fatigue

Evaluate against the PCRD of the QMP
- Ongoing evaluation of material quality substantiates the design allowable
- Only plausible way to maintain design values
Qualification & Certification/Qualified Metallurgical Process

PCRD

Process Margin ≥ 0

PCRD 99/95

DVS

DVS 99/95 (design)

Property

μ_witness

σ_witness

μ 1σ
Example of AM build witness specimen evaluations

Nominal process is **blue**, off nominal in **red**

Two (2) witness tests per build

Process shift hard to discern

Six (6) witness tests per build

Process shift discernable with analysis of mean and variation
Simulation is used to evaluate small sample statistical methods for witness specimen acceptance. Design acceptance criteria for the following:

- Keep process in family
- Minimize false negative acceptance results
- Protect the design values witnessed
- Protect the inferred design values
AM Design
Value Suite

Qualification & Certification/Witness for Statistical Process Control

Qualification & Certification/Witness for Statistical Process Control

Registration

AM Design Value Suite

Characterization builds

Part builds

PCRD consistent with PCRD

PCWS

Test Specimens

PCWS

First Article/WS
• **AM Does not need to be unique in certification approach**
  – Technology advances may bring unique opportunities

• For NASA, standardization in AM qualification is needed
  – Eventually, just part of Materials & Processes, Structures, Fracture Control standards

• Provides a consistent set of products
  – Consistent evaluation of AM implementation and controls
  – Consistent evaluation of risk in AM parts

• Details Discussed:
  – Part Classification of considerable value to certifying body
    • Rapid insight, communicate risk
  – Qualified Metallurgical Process is foundational
  – Witness testing for process control needs to be intelligent
There is more to AM than manufacturing

*AM machines create a unique material product form – typically purview of the foundry or mill*

Subtractive Forging Process

1. Ingot Making
2. Cutting
3. Heating
4. Forging
5. Heat Treating
6. Machining
7. Inspection
8. Delivery with CoC

Additive SLM Process

1. Powder Making
2. Printing
3. HIPing
4. Heat Treating
5. Machining
6. Inspection
7. Final Part

As the ‘mill’, the AM process must assure manufacturing compliance throughout the build process and material integrity throughout the volume of the final part.
AM responsibility serving as the material mill gives rise to additional reliability concerns
- Low entry cost compared to typical material producers
- New players in AM, unfamiliar with the scope of AM, lacking experience
- Fabrication shops not previously responsible for metallurgical processes
- Research labs converting to production

AM machines operate with limited process feedback!
- Reliability depends upon the quality and care taken in every step of AM operations => rigorous and meticulous controls

Concept Laser X-line Material Mill in a Box
Why Standards?

OMB A-119

Thursday
February 19, 1998

Part IV

Executive Office of
the President
Office of Management and Budget

OMB Circular A-119; Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities; Notice

• NASA: improve mission reliability and safety
• Industry: boost business and develop technology for American commerce

• Agencies must consult with voluntary consensus standards bodies, and must participate with such bodies in the development of voluntary consensus standards when consultation and participation is in the public interest

• If development of a standard is impractical or infeasible, the agency must develop an explanation of the reasons for impracticality and the steps necessary to overcome the impracticality

• Any standards developed must be necessarily non-duplicative and noncompetitive
Similar NDE of AM U.S./E.U. Efforts

- Status on ISO TC 261 JG 59 standard for NDT of AM products

ASTM E07.10 WK47031 NDT of AM Guide

- First VCO catalogues of AM defects showing Defect ↔ NDE linkage
- No agreement between ISO TC261 JG59 and E07 to develop joint standards
- ASTM WK47031 references U.S. standards; ISO standard references ISO standards

Guide for NDE of As-built and Post-Processed Metal AM Parts (WK56649)