Nondestructive Testing of Additive Manufactured Metal Parts Used in Aerospace Applications

Jess M. Waller · NASA-JSC WSTF

ASTM International Webinar

Session I, Tuesday, February 6, 2018
Session II, Tuesday, February 13, 2018
1:00 to 2:00 p.m. EST
• NDE inspectors, QA/QE professionals, and program managers responsible for the out-sourcing, procurement, fabrication, finishing, inspection, and qualification and certification of additively manufactured (AM) parts should attend this course.

• Review current best practices for NDE of metal AM parts.

• Learn about the challenges associated with NDE-based qualification and certification of AM parts.

• Survey important AM defect types and learn how defects are determined by material, processing, and post-processing.

• Learn how to apply NDE based on processing, defect types present, post-processing, structural margin, part complexity, and part criticality.

• Provide the end user basic tools to control OEMs and ensure the full, reliable, and safe use of this technology.
INSTRUCTOR

• B.S. in Chemistry from the University of North Carolina at Chapel Hill (1984); Ph.D. in Polymer Science from the University of Akron (1994); 23 of 29 years of work experience focused on aerospace materials at the NASA-JSC White Sands Test Facility in Las Cruces, New Mexico.

• Member of ASTM Committee E07 on Nondestructive Testing, F42 on Additive Manufacturing Technologies, D20 on Plastics, D30 on Composite Materials, and G04 on Sensitivity of Materials in Oxygen-Enriched Atmospheres.

• Chairman of the ASTM E07.10 Taskgroup on Nondestructive Testing of Aerospace Materials.

• Currently serving on the American Makes/ANSI Additive Manufacturing Standards Collaborative (AMSC) NDE, Qualification & Certification, Process Control, and Design Working Groups.
1:00-1:10  • Overview and introduction .......................... 1-8
1:10-1:50  • Background, AM aerospace hardware examples ............ 9
• Relevant NIST, USAF, and NASA documentation ........ 16
• NDE of AM technology gaps ..................................... 27
• Challenges and promising developments in NDE-based quality assurance of AM parts ................................. 40
• AM defect types .......................................................... 44
• Emerging voluntary consensus standards guidance ........ 54
  – ANSI-America Makes Additive Manufacturing Standardization Collaborative (AMSC) Roadmap ........ 60
  – NDE Gaps ............................................................... 67
  – Qualification & Certification Gaps ............................. 70
  – ASTM/ISO Standards in Development or Planned ...... 71
    • ASTM E07/F42-ISO TC 261 Collaboration .................... 76
    • Defect Terminology ................................................. 78
    • Seeded Flaws ......................................................... 79
    • Nondestructive Testing of AM Parts ......................... 81
    • In-Process Monitoring of AM Parts ............................ 92
1:50-2:00  • Quiz for understanding
<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:00-1:15</td>
<td>- Physical Reference Standards</td>
</tr>
<tr>
<td></td>
<td>NASA physical reference standards</td>
</tr>
<tr>
<td></td>
<td>Concept Laser CT reference standards</td>
</tr>
<tr>
<td></td>
<td>MTC Star and air foil artefacts</td>
</tr>
<tr>
<td>1:15-1:30</td>
<td>- Applying NDE to understand effect-of-defect</td>
</tr>
<tr>
<td></td>
<td>ASTM round robin NDE</td>
</tr>
<tr>
<td></td>
<td>Round Robin test samples</td>
</tr>
<tr>
<td></td>
<td>Round Robin test results (illustrative)</td>
</tr>
<tr>
<td>1:30-1:50</td>
<td>- NASA MSFC’s Qualification and Certification of AM Spaceflight Hardware</td>
</tr>
<tr>
<td></td>
<td>NASA Part Classification</td>
</tr>
<tr>
<td></td>
<td>LMCO Part Classification</td>
</tr>
<tr>
<td></td>
<td>NASA MFSC Qualified Metallurgical Process</td>
</tr>
<tr>
<td></td>
<td>Spaceflight hardware process control</td>
</tr>
<tr>
<td></td>
<td>AM part variability</td>
</tr>
<tr>
<td></td>
<td>General spaceflight hardware NDE considerations</td>
</tr>
<tr>
<td>1:50-2:00</td>
<td>- Quiz for understanding</td>
</tr>
</tbody>
</table>
• An emphasis is placed on the current NDE state-of-the-art inspection methods for metal AM parts used in fracture critical aerospace applications.

• For completeness, will address some of the latest advances in additively manufactured plastic AM parts used in non-fracture critical aerospace applications.
READY?!
On paper, the merits of additive manufacturing are compelling. For example, because of real (and perceived) gains:

- reduced waste
- simpler (fewer welds) yet highly optimized designs (topology optimization)
- reduced production lead time
- lighter weight

AM parts are being actively considered at NASA and its commercial space partners for flight critical rocket engine and structural applications.

However, numerous technology gaps prevent full, reliable, and safe use of this technology. Important technology gaps are:

- integrated process control (in-situ monitoring during build)
- material property controls (input materials, qualified material processes)
- mature process-structure property correlations (design allowables data)
- mature effect-of-defect (includes fracture mechanics)
- mature quality control measures (includes NDE tailored to AM)
NASA's rocket injectors manufactured with traditional processes would take more than a year to make, but with new 3D printing processes, the parts can be made in less than four months, with a 70 percent reduction in cost.

Using traditional manufacturing methods, 163 individual parts would be made and then assembled. But with 3D printing technology, only two parts were required, saving time and money and allowing engineers to build parts that enhance rocket engine performance and are less prone to failure.

SpaceX has been focusing on executing test flights of the Dragon spacecraft which is designed to carry astronauts as the company prepares to launch human-based space exploration missions.

“Through 3D printing, robust and high-performing engine parts can be created at a fraction of the cost and time of traditional manufacturing methods,” said Elon Musk, Chief Designer and CEO.

The Dragon thrusters, known as SuperDraco Rocket Engines, are 3D-printed using an EOS metal 3D Printer and are made from Inconel®. “It’s a very complex engine, and it was very difficult to form all the cooling channels, the injector head, and the throttling mechanism. Being able to print very high strength advanced alloys … was crucial to being able to create the SuperDraco engine as it is.”

http://www.spacex.com/press/2014/05/27/spacex-completes-qualification-testing-superdraco-thruster
GE Aviation will install 19 fuel nozzles into each Leading Edge Aviation Propulsion (LEAP) jet engine manufactured by CFM International, which is a joint venture between GE and France’s Safran Aircraft Engines. CFM has orders for 6000 LEAPs (40,000 by 2020).

**Lighter** – the weight of these nozzles will be 25% lighter than its predecessor part.

**Simpler design** – reduced the number of brazes and welds from 25 to 5.

**New design features** – more intricate cooling pathways and support ligaments will result in $5\times$ higher durability vs. conventional manufacturing.

“Today, post-build inspection procedures account for as much as 25 percent of the time required to produce an additively manufactured engine component,” said Greg Morris, GE Aviation's business development leader for AM. “By conducting those inspection procedures while the component is being built, (we) will expedite production rates for GE’s additive manufactured engine components like the LEAP fuel nozzle.”

GE Aviation successfully completed the first engine test in Prague, Czech Republic, in December 2017 of its advanced turboprop (ATP) engine, the first clean-sheet turboprop engine to hit the Business and General Aviation (BGA) market in more than 30 years. The ATP engine is the first aircraft engine in history with a large portion of parts made by additive manufacturing.

Lighter – The engine is 5 percent lighter.

Simpler design – 855 separate parts reduced to 12.

More efficient – Lighter weight means the aircraft will use less fuel to attain the same speed (the ATP burns 20 percent less fuel and achieves 10 percent more power than its competitors).

Lower maintenance – Fewer assembled parts and opportunities for wear.

Unprecedented use of additive manufacturing – More than a third of the ATP is 3D-printed from advanced alloys.

“... the ATP is going from a dream to a reality in just two years,” says Gordie Follin, the executive manager of GE Aviation’s ATP program. “With additive manufacturing, we’re disrupting the whole production cycle” Follin says.
Engineers successfully hot-fire tested an RS-25 rocket engine in December 2017 modified with a large beach ball-sized 3D-printed part, called the pogo accumulator, which acts as a shock absorber by regulating liquid oxygen movement in the engine to prevent the vibrations from desabilizing a rocket’s flight. The test marked a key step toward reducing costs for future engines that power NASA’s new heavy-lift rocket, the Space Launch System.

Simpler, more affordable – more than 100 welds were eliminated in the accumulator, reducing costs by nearly 35 percent and production time by more than 80 percent.

“Reducing the number of welds is very important," said Carol Jacobs, RS-25 engine lead at Marshall. "With each weld comes inspections and possible rework. By eliminating welds, we make the hardware more reliable and the process much more lean and efficient, which makes it more cost-effective.”
• America Makes, ANSI, ASTM, NASA and others are providing key leadership in an effort linking government and industry resources to speed adoption of aerospace AM parts.

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

• NDE is identified as a universal need for all aspects of additive manufacturing.
BACKGROUND

- NDE has been identified as a universal need spanning all aspects of additive manufacturing, from process control, to generation of design allowables data, to qualification and certification of flight hardware.
- Given NASA’s focus is often on high value, limited production quantity parts and prototype designs, destructive tests and large batch runs to validate designs, processes, and materials aren’t always feasible, leaving NDE as the only effective way to ensure these parts meet necessary NASA requirements.
- Given the unique defect types (for example, porosity, trapped powder, and lack of fusion) and the lack of mature effect-of-defect data for AM parts, predictive models do not yet exist for part acceptance. Subject matter experts from NDE and materials must develop techniques to characterize defects, determine their effect on performance, learn how to reliably detect and screen for defects, in order to qualify parts for use.
Key Documents to Improve Reliability and Safety of Metal AM Parts

NASA Additive Manufacturing Roadmap and NDE-related Technology Gaps
Key NASA AM Qualification & Certification Documents (cont.)

- **EM20**: MSFC Technical Standard
  - **July 2015**: Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware
  - **October 18, 2017**: Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals
  - **EM20**: Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes
NASA Engineering and Safety Center (NESC) publicity:

Development of NASA Standards for Enabling Certification of Additively Manufactured Parts

There are currently no NASA standards providing specific design and construction requirements for certification of additively manufactured parts. Several international standards organizations are developing standards for additive manufacturing; however, NASA mission schedules preclude the Agency from relying on these organizations to develop standards that are both timely and applicable. NASA and its program partners in manned spacecraft (the Commercial Crew Program, the Space Launch System, and the Orion Multi-Purpose Crew Vehicle) are actively developing additively manufactured parts for flight as early as 2018. To bridge this gap, NASA Marshall Space Flight Center (MSFC) has authored a Center-level standard (MSFC-STD-3716) to establish standard practices for the Laser Powder Bed Fusion (LPBF) process. In its initial form, the MSFC standard has been used as a basis for LPBF process implementation for each of the human spaceflight programs. The development of an Agency-level standard is proposed, based upon the principles of MSFC-STD-3716, which would have application to multiple additive manufacturing processes and be readily adaptable to all NASA programs.

Background

Additive manufacturing (AM) has rapidly become prevalent in aerospace applications. AM offers the ability to rapidly manufacture complex part designs at a reduced cost; however, the extreme pace of AM implementation introduces risks to the safe adoption of this developing technology. The development of aerospace quality standards and specifications is required to properly balance the benefits of AM technologies with the inherent risks. NASA design and construction standards do not yet include specific requirements for controlling the unique aspects of the AM process and resulting hardware. While a significant national effort is now focused on creating standards for AM, the current and scheduled release of these consensus standards do not support the near-term programmatic needs of NASA.

MSFC Standard and Application to Human Spaceflight Hardware

NASA MSFC has led the development of a Center-level standard, MSFC-STD-3716, to aid in the development of standard practices for LPBF processes. This standard and its companion specification, MSFC-SPEC-2717, provide a consistent framework for the development, production, and evaluation of additively manufactured parts for spaceflight applications. The standard contains requirements addressing material property development, part classification, part process control, part inspection, and acceptance. The companion specification provides requirements for qualification of LPBF metallurgical processes, equipment process control, and personnel training. Engineering from the three active manned spaceflight programs have used the MSFC standard as a guideline for implementation of AM parts, ensuring partners establish reliable AM processes and meet the intent of all NASA standards in materials, fracture control, nondestructive evaluation, and propulsion structures.

Path Forward to an AM Standard

In addition to human spaceflight, standards for appropriate application of AM to other NASA missions such as science and aeronautics require consideration. Full embrace of AM technologies requires standardization beyond the Poweder Bed Fusion process. A planned Agency standard applicable to all NASA programs and most AM technologies is currently being explored. Proper standardization is key to enabling the innovative promise of AM, while ensuring safe, functional, and reliable AM parts.

References


For information contact the NESC at www.nasa.gov

Other Key AM Documents (Roadmaps) (cont.)

- CAMM Consortium for Additive Manufacturing Materials
  - Strategic Roadmap for the Next Generation of Additive Manufacturing Materials
    - December 2015

- America Makes
  - Standardization Roadmap for Additive Manufacturing
    - VERSION 1.0
    - February 2017

- ANSI American National Standards Institute
  - Measurement Science Roadmap for Polymer-Based Additive Manufacturing
    - December 2016

- NIST Advanced Manufacturing Series 100-5

- = discussed in this course
Contact: Kevin Jurrens (NIST)

• Lists technology challenges impeding adoption of AM.
• Measurement and monitoring techniques, including NDE, cut across all aspects of AM, from input materials to processing to finished parts.
• Ways to fully characterize AM parts, including NDE, are needed to insure processing effectiveness and part repeatability (part certification).
• NASA participation:
  o Matt Showalter, GSFC
  o Karen Taminger, LaRC
  o Gary Wainwright, LaRC
  o Nancy Tolliver, MSFC

NIST Roadmap for Metal-Based AM

Important Technology and Measurement Challenges for AM

- Cross-cutting needs for NDE
- Highly influential in development of 2014 NASA State-of-the-Discipline Report
Contact: Evgueni Todorov (EWI)

- Early results on NDE application to AM are documented.
- Report has a ranking system based on geometric complexity of AM parts to direct NDE efforts.
- Approach laid out for future work based on CT and PCRT and other NDE techniques.

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):

<table>
<thead>
<tr>
<th>NDE Technique</th>
<th>Common Acronym</th>
<th>Material and Flaw Types Detected</th>
<th>Surface or Interior</th>
<th>Global Screening or Detect Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Testing</td>
<td>VT</td>
<td>In any solid material, any condition and/or defect affecting visual light reflection.</td>
<td>Surface</td>
<td>Detects and images location</td>
</tr>
<tr>
<td>Leak Testing</td>
<td>LT</td>
<td>Solid material. Discontinuities.</td>
<td>Through thickness</td>
<td>Detects location</td>
</tr>
<tr>
<td>Liquid Penetrant Testing</td>
<td>PT</td>
<td>Any solid material. Discontinuities - cracks, pores, nicks, others.</td>
<td>Surface breaking</td>
<td>Detects and images location</td>
</tr>
<tr>
<td>Process Compensated Resonance Testing</td>
<td>PCRT</td>
<td>Any solid material. Any defect or condition.</td>
<td>Surface and subsurface</td>
<td>Global screening</td>
</tr>
<tr>
<td>Impedance computed tomography or</td>
<td>ICT or EIT</td>
<td>In electrically conductive material, any condition and/or defect affecting electrical conductivity.</td>
<td>Surface and subsurface</td>
<td>Detects and images location</td>
</tr>
<tr>
<td>Electrical impedance tomography</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternate Current Potential Drop</td>
<td>ACPD</td>
<td>In electrically conductive material, any condition and/or defect affecting electrical conductivity.</td>
<td>Surface and subsurface</td>
<td>Detects location</td>
</tr>
<tr>
<td>Eddy Current Testing</td>
<td>ET</td>
<td>In electrically conductive material any condition and/or defect affecting electrical conductivity, magnetic permeability and/or sensor-part juxtaposition</td>
<td>Surface and slightly subsurface</td>
<td>Detects location</td>
</tr>
</tbody>
</table>

- Optical Method (OM)
- parts where liquid/gas leak tightness reqd.
- post-machining reqd., line of sight issues
- ASTM E2534
- correlate $R, \sigma$ with mechanical props
- correlate $\sigma$ with microstructure and residual stresses
- measurement of compressive elastic stresses by peening
<table>
<thead>
<tr>
<th>NDE Technique</th>
<th>Common Acronym</th>
<th>Material and Flaw Types Detected</th>
<th>Surface or Interior</th>
<th>Global Screening or Detect Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array Eddy Current Testing</td>
<td>AEC</td>
<td>In electrically conductive material any condition and/or defect affecting electrical conductivity, magnetic permeability and/or sensor-part juxtaposition.</td>
<td>Surface and slightly subsurface</td>
<td>Detects and images location</td>
</tr>
<tr>
<td>Phase Array Ultrasonic Testing</td>
<td>PAUT</td>
<td>In any solid material, any condition and/or defect affecting sound attenuation, propagation, acoustic velocity and/or sensor-part juxtaposition.</td>
<td>Surface and subsurface</td>
<td>Detects and images location</td>
</tr>
<tr>
<td>Ultrasonic Testing</td>
<td>UT</td>
<td>In any solid material, any condition and/or defect affecting sound attenuation, propagation, acoustic velocity and/or sensor-part juxtaposition.</td>
<td>Surface and subsurface</td>
<td>Detects location</td>
</tr>
<tr>
<td>Radiographic Testing</td>
<td>RT</td>
<td>In any solid material, any condition and/or defect affecting X-ray absorption.</td>
<td>Surface and subsurface</td>
<td>Detects and images location</td>
</tr>
<tr>
<td>X-Ray Computed Tomography</td>
<td>X-Ray CT</td>
<td>In any solid material, any condition and/or defect affecting X-ray absorption.</td>
<td>Surface and subsurface</td>
<td>Detects and images location</td>
</tr>
<tr>
<td>Microfocus X-Ray Computed Tomography</td>
<td>X-ray MicroFCT</td>
<td>In any solid material, any condition and/or defect affecting X-ray absorption.</td>
<td>Surface and subsurface</td>
<td>Detects and images location</td>
</tr>
</tbody>
</table>

- **Array Eddy Current Testing**: fast scanning of large areas with minimal sweeps, detection of defects influenced by microstructure, grain size, anisotropy.
- **Phase Array Ultrasonic Testing**: surface adaptive UT for complex shapes, use advanced time reversal focusing algorithms.
- **Ultrasonic Testing**: influenced by microstructure, grain size, anisotropy.
- **Radiographic Testing**: inspection of Group 1 and 2, and limited application for Group 3.
- **X-Ray Computed Tomography**: broad in-house NASA capability.
<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>
<tr>
<td>PCRT</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>EIT</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>ACPD</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>ET</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>AEC</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>PAUT</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>UT</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>RT</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>X-Ray CT</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>X-ray Micro CT</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

**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

---

Contacts: Jess Waller (WSTF); James Walker (MSFC); Eric Burke (LaRC); Ken Hodges (MAF); Brad Parker (GSFC)

- NASA Agency additive manufacturing efforts through 2014 were catalogued.
- Industry, government and academia were asked to share their NDE experience on AM parts.
- NDE state-of-the-art was documented.
- NIST and USAF additive manufacturing roadmaps were surveyed and a technology gap analysis performed.
Inconel Pogo-Z baffle for RS-25 engine for SLS

Reentrant Ti6-4 tube for a cryogenic thermal switch for the ASTRO-H Adiabatic Demagnetization Refrigerator

EBF$^3$ wire-fed system during parabolic flight testing

Prototype titanium to niobium gradient rocket nozzle

Made in Space AMF on ISS

ISRU regolith structures

Aerojet Rocketdyne RL-10 engine thrust chamber assembly and injector

Dynetics/Aerojet Rocketdyne F-1B gas generator injector

SpaceX SuperDraco combustion chamber for Dragon V2

28-element Inconel 625 fuel injector
JPL Mars Science Laboratory Cold Encoder Shaft fabricated by gradient additive processes

MSFC rocket engine fuel turbopump with 45 percent fewer parts than pumps made with traditional manufacturing

MSFC copper combustion chamber liner for extreme temperature and pressure applications

NASA STMD-sponsored Cube Quest challenge for a flight-qualified cubesat (shown: cubesat with an Inconel 718 additively manufactured diffuser section, reaction chamber, and nozzle)

Additive Manufacturing Structural Integrity Initiative (AMSII) Alloy 718 powder feedstock variability

One-piece as-built (left) and post-processed (right) rocket engine injector made in 40 hours at NASA MSFC

NASA-sponsored 3-D Printed Habitat Challenge Design Competition
• Involves the characterization of defect structures in laser powder bed fusion (L-PBF) Inconel® 718 parts made within nominal and off-nominal process windows, building of test articles for NDE, and correlation of with destructive test results.

• Relevance to parts made for Commercial Crew Program (CCP), Space Launch System (SLS) and Multipurpose Crew Vehicle (MPCV).
NASA’s Marshall Space Flight Center (MSFC) AM injector was successfully hot-fire tested by Vector Space System on Dec. 8, 2016 using liquid oxygen/propylene propellant (LOX/LC$_3$H$_6$).

(work performed under a 2015 NASA Space Technology Mission Directorate Space Act Agreement)
Fracture critical damage tolerant metal AM hardware must meet NDE requirements given in NASA-STD-5009; however, the 5009 90/95 POD flaw types and sizes are generally inappropriate for AM.

Table 2—Minimum Detectable Crack Sizes for Fracture Analysis Based on Standard NDE Methods (Metric Version) (See “Conditional Notes,” section 4.2.3 for applicability.)

<table>
<thead>
<tr>
<th>Crack Location</th>
<th>Part Thickness, t</th>
<th>Crack Type</th>
<th>Crack Dimension, a</th>
<th>Crack Dimension, c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Surface</td>
<td>t ≤ 1.27</td>
<td>Through</td>
<td>0.51</td>
<td>2.54</td>
</tr>
<tr>
<td></td>
<td>t &gt; 1.27</td>
<td>Through</td>
<td>1.27</td>
<td>1.27</td>
</tr>
<tr>
<td>Edge or Hole</td>
<td>t ≤ 1.91</td>
<td>Through</td>
<td>1.91</td>
<td>1.91</td>
</tr>
</tbody>
</table>

Pencil NDE

<table>
<thead>
<tr>
<th>Crack Location</th>
<th>Part Thickness, t</th>
<th>Crack Type</th>
<th>Crack Dimension, a</th>
<th>Crack Dimension, c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Surface</td>
<td>t ≤ 1.27</td>
<td>Through</td>
<td>0.64</td>
<td>3.18</td>
</tr>
<tr>
<td></td>
<td>t &gt; 1.27</td>
<td>Through</td>
<td>1.91</td>
<td>1.91</td>
</tr>
<tr>
<td>Edge or Hole</td>
<td>t ≤ 2.54</td>
<td>Through</td>
<td>2.54</td>
<td>3.81</td>
</tr>
</tbody>
</table>

Magnetic Particle NDE

<table>
<thead>
<tr>
<th>Crack Location</th>
<th>Part Thickness, t</th>
<th>Crack Type</th>
<th>Crack Dimension, a</th>
<th>Crack Dimension, c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Surface</td>
<td>t ≤ 1.91</td>
<td>Through</td>
<td>0.97</td>
<td>4.78</td>
</tr>
<tr>
<td></td>
<td>t &gt; 1.91</td>
<td>Through</td>
<td>1.91</td>
<td>3.38</td>
</tr>
<tr>
<td>Edge or Hole</td>
<td>t ≤ 1.91</td>
<td>Through</td>
<td>1.91</td>
<td>6.35</td>
</tr>
</tbody>
</table>

Radiographic NDE

<table>
<thead>
<tr>
<th>Crack Location</th>
<th>Part Thickness, t</th>
<th>Crack Type</th>
<th>Crack Dimension, a</th>
<th>Crack Dimension, c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Surface</td>
<td>t ≤ 2.72</td>
<td>PTC</td>
<td>0.71</td>
<td>1.91</td>
</tr>
<tr>
<td></td>
<td>t &gt; 2.72</td>
<td>Embedded</td>
<td>0.71</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Ultrasonic NDE

Comparable to a Class A Quality Level (ASTM E-2375)

<table>
<thead>
<tr>
<th>Crack Location</th>
<th>Part Thickness, t</th>
<th>Crack Type</th>
<th>Crack Dimension, a</th>
<th>Crack Dimension, c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Surface</td>
<td>t ≥ 2.54</td>
<td>PTC</td>
<td>0.76</td>
<td>3.81</td>
</tr>
</tbody>
</table>

LOG

1. PTC = Partly through crack/Surface Crack
2. See figure 1 for definitions of “a” and “c” for different geometries.
3. Equivalent area is acceptable, ASTM E-2375 Class A.

§ NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components
AM poses unique challenges for NDE specialist:

- Complex part geometry (see AFRL-RX-WP-TR-2014-0162)
- Deeply embedded flaws and internal features
- Rough as-built surface finish (interferes with PT, ET)
- Variable, complex grain structure, or metastable microstructure
- Lack of physical reference standards with same material and processing history as actual AM parts (demonstrate NDE capability)
- Lack of effect-of-defect studies (using sacrificial defect samples)
- Methods to seed ‘natural’ flaws are still being developed
- High part anisotropy with 2D planar defects perpendicular to Z-direction
- Critical flaw types, sizes and distributions not established
- Defect terminology harmonization still occurring
- Process-specific defects can be produced, some unique to AM
- Little (any?) probability of detection (POD) data
- Lack of written NDE procedures for AM parts (focus area for this course)
- Lack of mature in-situ monitoring techniques
Initial NDE-related 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, sizes, and distributions.
- Develop **NDE-based qualification and certification protocols** for flight hardware (screen out critical defects).
Final NDE-related Gaps:

- Develop a 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
- 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)
NDE-related Technology Gaps:

First:
- Develop a **defect catalog**
- Develop **in-process NDE** to improve feedback control, maximize part quality and consistency, and obtain ready-for-use parts
- Develop and refine **NDE** used on parts after build
- 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** (phantoms or artifacts) to demonstrate NDE capability for specific features or defect types
- Apply NDE to **understand effect-of-defect**, and establish acceptance limits for specific defect types and defect sizes

Somewhere in the middle:
- Develop **NDE-based qualification and certification protocols** for flight hardware (screen out critical defects)
Contact: **PSU CIMP-3D**

- Covers metal, polymer, and ceramic AM processing.
- AM applications rely on feedstocks which have not been optimized for AM.
- Industry must develop new materials and feedstock's specifically tailored for AM to realize advantages in next generation applications and designs.
- Focuses on basic research (TRL1-3) to promote the introduction of new AM materials.
- Use of NDE to analyze processes mentioned.
- Processing framework useful for differentiating NDE after built.
Role of NDE in Process Analytics

- Effect of process parameters (scanning pattern, power, speed, and build direction) on 316L stainless steel parts were evaluated using nondestructive evaluation (neutron diffraction) to measure the residual stress after build, allowing selection of parameters yielding the least amount of residual stress in L-PBF parts. 


CAMM Thrust Areas:
1: Integrated Design for Materials, Processes, and Parts
2: Process-Structure-Property (PSP) Relationships
3: Part and Feedstock Test Protocols (e.g., micromechanics, not NDE)
4: AM Process Analytics (e.g. in-situ monitoring)
5: Next-Generation AM M&P

CAMM Roadmap for Metal-Based AM (2015)
In addition to making highly complex parts, AM part microstructure, hence properties, can be customized by varying process parameters to control melt pool characteristics, solidification rates, rheology, and feedstock deposition rates.

---

CAMM Roadmap for Metal-Based AM / Processing Methods

In addition to making highly complex parts, AM part microstructure, hence properties, can be customized by varying process parameters to control melt pool characteristics, solidification rates, rheology, and feedstock deposition rates.
Breakout sessions held for NDE, Supplier/OEM Auditing and Qualification, Powder Quality, and Industry/Academic Partnerships
Key development areas, challenges and promising work relative to were captured in the NDE Breakout Session.

Key development areas identified for NDE are:

1. A defect catalog
2. Effect-of-defect studies
3. Acceptance criteria
4. NDE capability at the critical flaw size for high value fracture critical parts
5. NDE protocols for first articles vs. witness coupons vs. spares vs. production parts

The bad news is there are many challenges are associated with 1-5 above; the good news is there are promising developments in each of the above areas.
1. **Defects catalog**
   - Terminology harmonization
   - Chemical and microstructural differences between reference and production parts.

2. **Effect-of-defect studies**
   - Is costly, load share and collaboration desirable to minimize cost burden
   - Which flaws are important or critical?
   - How to fabricate those flaws reliably and controllably?
   - Are flaws in sacrificial parts representative of those in production parts?
   - Effect of HIP, heat treatment on NDE detection of flaws (worst flaw may not be obvious)

3. **Acceptance criteria**
   - Part-specific vs. universal, proprietary obstacles
   - What are the acceptance thresholds for a given flaw type (fracture mechanics guidance)?
   - Potential misuse of NASGRO in determining critical initial flaw size and subsequent growth.
   - What is the influence of flaw homogeneity on acceptance (surface vs. sub-surface)?
   - What to do about deeply embedded flaws that might be missed?
   - Location and zoning of defects using thermal models (where do I need to inspect?)
   - Conventional crack growth analysis mature; analytical models for AM flaw growth are lacking.

4. **NDE capability at the critical flaw size for high value, fracture critical parts?**
   - Is focus on natural (porosity, LOF, voids) or idealized flaws (cubic/spherical voids, phantoms)?
   - How statistically significant does the NDE need to be (90/95 POD or something else)?
   - NDE detectability for 2D planar flaws?
   - NDE for unique L-PBF flaw types (LOF, layer, cross layer and trapped powder) have not been necessarily developed

5. **NDE protocols will differ for first articles, witness coupons, spares, and production parts**
1. **Defects catalog**
   - Proposed ASTM/ISO 52900 terminology and/or pictorial defect catalog in progress.
   - Allow in-situ monitoring to catch up to guide NDE.
   - Process simulation using thermal models (e.g., NRL, Wayne King at LLNL) to guide NDE.

2. **Effect-of-defect studies**
   - NASA-Industry efforts (ASTM WK47031 ILS, UTC/Southern Research)
   - JPL-Carnegie Mellon effort
   - ONR Quality MADE effort

3. **Acceptance criteria**
   - Look at VW-50097 Design Standard for cast parts (E.U. ‘Bible’)
   - AMS 2175 Parts A-D for aerospace components
   - ASTM RT standard for reference radiographs (parent radiographic standard is ASTM E1742 (2-T sensitivity))

4. **NDE capability at the critical flaw size for high value, fracture critical parts?**
   - Emerging NDE techniques (PCRT) whole body pass/fail of (esp. for complex AM parts)
   - Acoustic emission whole body pass/fail
   - Neutron diffraction for frozen-in stress (ORNL)

5. **NDE protocols for first articles, witness coupons, spares, and production parts**
   - MSFC-STD-3716 and MSFC-SPEC-3717 baseline guidance
   - Lockheed Martin tiered NDE doe AM parts categories
Develop a defects catalogue
• Develop a **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
• 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)
Causes

- Beam degradation
- Beam power too high
- Powder charging explosion
- Powder ablation movement
- Excess layer thickness
- Powder contamination
- High angle grain boundaries
- Freckling
- Overhanging feature heat distribution
- Ductility dip
- Changes in wetting angle

Defects (DED & PBF)

- Voids
- Incomplete fusion
- Non-uniform weld beads & fusion characteristic
- Amorphous defect (inter/intra-layer)
- Unconsolidated powder
- Undersuts
- Reduced mechanical properties
- Porosity
- Contamination or inclusion
- Steps in part
- Porosity
- Over or under melted material
- Trapped powder
- Poor surface finish

As-Processed Failure Mode

- Melt pool instability
- In build warping
- Material feed failure
- Over heating
- Powder charging
- Residual stress
- Ablation instability
- Under heating
- Microstructure failure

(Process) (Structure) (Property)
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.

![Image](image.png)

**Develop new NDE methods**

---

\[ ISO \text{ TC 261 JG59, Additive manufacturing – General principles – Nondestructive evaluation of additive manufactured products, under development.} \]

Note: DED = Directed Energy Deposition, PBF = Powder Bed Fusion
## Typical AM Defects and Causes

<table>
<thead>
<tr>
<th>Defect/effect on part</th>
<th>Issue</th>
<th>Why</th>
<th>In-process detection</th>
<th>Post process detection</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Porosity due to unconsolidated powder</strong></td>
<td>Incomplete powder feed</td>
<td>Powder run out Bridging of powder in the hopper / poor flow properties</td>
<td>Yes - check if powder is flowing from the feed hopper</td>
<td>Difficult to detect</td>
<td>HIP recoverable</td>
</tr>
<tr>
<td><strong>Layer/large area</strong></td>
<td>“Drags” (lines) in powder layer</td>
<td>Agglomerated powder or contamination</td>
<td>Vision system Laser scanning of layer</td>
<td>Very difficult to detect</td>
<td>HIP recoverable</td>
</tr>
<tr>
<td><strong>Layer/unconsolidated powder</strong></td>
<td>Poor fusion due to interruption to laser/EBM delivery</td>
<td>Interruption to powder supply, optics systems errors (laser) or errors in data.</td>
<td>View fusing using IR cameras or back scatter methods</td>
<td>Difficult – very difficult to detect depending on magnitude</td>
<td>HIP recoverable</td>
</tr>
<tr>
<td><strong>(localised area)</strong></td>
<td>Incorrect laser/EBM power</td>
<td>Incorrect choice of parameters Uncontrolled change in laser/EBM power</td>
<td>Yes – if have in-line measurement of power</td>
<td>Tell tale signs on the part provided that the effect is not transient</td>
<td>Should be a relatively easy fix</td>
</tr>
<tr>
<td><strong>Layer shift/unconsolidated powder (large or small areas)</strong></td>
<td>Layer shift</td>
<td>SLM - scan head/ optics problems EMF – presence of EMF Build platform shift</td>
<td>Beam sensors may reduce the risk but best method is to compare the laser of EBM trace with the desired slice pattern</td>
<td>Usually easy as part has step on surface (but localised defects may go unnoticed)</td>
<td></td>
</tr>
<tr>
<td><strong>Over or under melted material</strong></td>
<td>Contamination of powder (interstitials)</td>
<td>New powder out of spec or degraded through reuse</td>
<td>Almost impossible</td>
<td>Check powder at end of process and mechanical properties / level of contamination of fused parts</td>
<td>Need to check the powder before use</td>
</tr>
<tr>
<td><strong>Inclusion/steps in part</strong></td>
<td>Contamination of powder (foreign body)</td>
<td>Debris from AM or post processing equipment</td>
<td>Almost impossible</td>
<td>Depends on the nature of the contamination May be able to detect using ultrasound / Xray, X-ray CT</td>
<td>Remove all potential sources of contamination Sieve / analyse powder to check</td>
</tr>
<tr>
<td><strong>Reduced mechanical properties (may get higher modulus but lower elongation)</strong></td>
<td>Incorrect scaling/beam offset</td>
<td>Scaling/offset factors are affected by part geometry, beam intensity and the density of the powder bed</td>
<td>Difficult Need method of very accurately tracking the position of the laser/EBM or the edge of the consolidated powder</td>
<td>Just measure the part Or benchmark</td>
<td></td>
</tr>
<tr>
<td><strong>Incorrect scan strategy</strong></td>
<td>Poor selection of parameters Errors in the precision of beam delivery</td>
<td>May be difficult to detect – can be quite subtle but leads to major defects. Sometime shown as gaps/holes in the layer as it is being formed – this could be detected by IR monitoring</td>
<td>Depends on the nature of the contamination May be able to detect using ultrasound / Xray, X-ray CT</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Porosity depends on the type of contamination</strong></td>
<td>Gas atomised powder particles</td>
<td>Contain entrapped gas bubbles</td>
<td>Almost impossible</td>
<td>Could be observed by OM or SEM but difficult to be distinguished from other types of pores</td>
<td>HIP recoverable</td>
</tr>
<tr>
<td><strong>Poor accuracy</strong></td>
<td>Poor localised layer surface quality</td>
<td>Localised disturbance of molten pool/lack of molten material feeding at some localised area</td>
<td>Almost impossible</td>
<td>Could be detected by OM or SEM</td>
<td>HIP recoverable</td>
</tr>
<tr>
<td><strong>Voids/unconsolidated powder</strong></td>
<td>Development of high internal stress in some types of materials</td>
<td></td>
<td>May be detected by IR monitoring</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Courtesy of AMAZE an FP7 EU project [http://www.amaze-project.eu/](http://www.amaze-project.eu/)
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

PBF Porosity

DED Porosity

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** — 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 NDE 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** — 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.
# Selection of NDE for Defect Detection

## Table 4.3 Application of NDT to Detect Additive Manufacturing Defect Classes

<table>
<thead>
<tr>
<th>Defect Class</th>
<th>CT/RT/CR/DR</th>
<th>ECT</th>
<th>MET</th>
<th>PCRT</th>
<th>PT</th>
<th>TT</th>
<th>UT</th>
<th>AE</th>
<th>LT</th>
<th>ND</th>
<th>MT</th>
<th>VT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>X&lt;sup&gt;c&lt;/sup&gt;</td>
<td>X&lt;sup&gt;d&lt;/sup&gt;</td>
<td>X</td>
<td>...</td>
<td>X&lt;sup&gt;d&lt;/sup&gt;</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>X</td>
</tr>
<tr>
<td>Porosity</td>
<td>X</td>
<td>X&lt;sup&gt;d&lt;/sup&gt;</td>
<td>...</td>
<td>X</td>
<td>X&lt;sup&gt;d&lt;/sup&gt;</td>
<td>...</td>
<td>X</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>X&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cracking</td>
<td>X</td>
<td>X&lt;sup&gt;d&lt;/sup&gt;</td>
<td>...</td>
<td>X</td>
<td>X&lt;sup&gt;d&lt;/sup&gt;</td>
<td>X</td>
<td>X</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Lack of Fusion</td>
<td>X</td>
<td>X&lt;sup&gt;d&lt;/sup&gt;</td>
<td>...</td>
<td>X</td>
<td>X&lt;sup&gt;d&lt;/sup&gt;</td>
<td>X</td>
<td>X</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>X</td>
<td>...</td>
</tr>
<tr>
<td>Part Dimensions</td>
<td>X</td>
<td>...</td>
<td>X</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Density&lt;sup&gt;g&lt;/sup&gt;</td>
<td>X&lt;sup&gt;h&lt;/sup&gt;</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Inclusions&lt;sup&gt;l&lt;/sup&gt;</td>
<td>X&lt;sup&gt;i&lt;/sup&gt;</td>
<td>X&lt;sup&gt;d&lt;/sup&gt;</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>X</td>
<td>X</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>X</td>
</tr>
<tr>
<td>Discoloration</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>X</td>
<td>...</td>
</tr>
<tr>
<td>Residual Stress</td>
<td>...</td>
<td>X&lt;sup&gt;d,j&lt;/sup&gt;</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>X</td>
<td>...</td>
</tr>
<tr>
<td>Hermetic Sealing</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>X&lt;sup&gt;f&lt;/sup&gt;</td>
<td>...</td>
</tr>
</tbody>
</table>

---


<sup>b</sup> Includes Digital Imaging.

<sup>c</sup> Especially helpful when characterizing internal passageways or cavities (complex geometry parts) for underfill and overfill, or other internal feature not accessible to MET, PT or VT (including borescopy).

<sup>d</sup> Applicable if on surface.

<sup>e</sup> Macroscopic cracks only.

<sup>f</sup> If large enough to cause a leak or pressure drop across the part.

<sup>g</sup> Pycnometry (Archimedes principle).

<sup>h</sup> Density variations will only show up imaged regions having equivalent thickness.

<sup>i</sup> If inclusions are large enough and sufficient scattering contrast exists.

<sup>j</sup> Residual stress can be assessed if resulting from surface post-processing (for example, peening).

---

Defect Causes

- **Bulk Defects**
  - Lack of Fusion
    - Horizontal Lack of Fusion Defect
      - Insufficient Power, Splatter
      - Laser Attenuation
    - Vertical Lack of Fusion Defect
      - Large Hatch Spacing
      - Short Feed
  - Spherical Porosity
    - Keyhole
  - Welding Defects
    - Cracking

- **Surface Defects**
  - Worm Track
    - High Energy Core Parameters
    - Re-coater Blade interactions
  - Core Bleed Through
    - Small Core Offset
    - Overhanging Surface
  - Rough Surface
    - Laser Attenuation
    - Overhanging Surfaces
  - Skin Separation
    - Sub-Surface Defects
    - Detached Skin

- **Process Parameters**
- **In-Process Anomaly**
- **Material Property**

---

The list to the left is color coded to show the known causes of the defects.
Although some defects are tolerable, many result in the degradation of mechanical properties or cause the part to be out of tolerance.
Most defects can be mitigated by parameter optimization and process controls.

---

• **Bulk Defects**
  - Lack of Fusion
    - Horizontal Lack of Fusion Defect
      - Insufficient Power
      - Laser Attenuation, Splatter
    - Vertical Lack of Fusion Defect
      - Large Hatch Spacing
    - Short Feed
  - Spherical Porosity
    - Keyhole
  - Welding Defects
    - Cracking

• **Surface Defects**
  - Worm Track
    - High Energy Core Parameters
    - Re-coater Blade interactions
  - Core Bleed Through
    - Small Core Offset
    - Overhanging Surface
  - Rough Surface
    - Laser Attenuation
    - Overhanging Surfaces
  - Contour Separation
    - Sub-Surface Defects
    - Detached Skin

Defects are color coded to show the effect-of-defect on part performance.

Trade-offs were noted, for example, reducing the offset to eliminate the contour separation defects results in the hatch from the core bleeding through the contour. As a result the part will not look as smooth but will perform better.

• Degradation of Mechanical Properties
• Minor or No Observed effect on performance
• Out of Tolerance
• Unknown

---

Develop voluntary consensus standards for NDE of AM parts
• Develop a **defects catalogue**

• Develop **in-process NDE** to improve feedback control, maximize part quality and consistency, and obtain ready-for-use parts

• Develop **post-process NDE** of finished 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)
Why Standards?

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

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

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

• If development of a standard is impractical, 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.

• NASA: improve mission reliability and safety
• Industry: boost business and develop technology for American commerce
<table>
<thead>
<tr>
<th>Standards Development Organizations involved in AMSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM International</td>
</tr>
<tr>
<td>International Organization For Standardization</td>
</tr>
<tr>
<td>American Society of Mechanical Engineers</td>
</tr>
<tr>
<td>SAE International</td>
</tr>
<tr>
<td>American Welding Society</td>
</tr>
<tr>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>MITA - Medical Imaging &amp; Technology Alliance</td>
</tr>
<tr>
<td>Association for the Advancement of Medical Instrumentation</td>
</tr>
<tr>
<td>IPC - Association Connecting Electronics Industries</td>
</tr>
<tr>
<td>Metal Powder Industries Federation</td>
</tr>
</tbody>
</table>
3D Systems Corporation*
3M
Alcoa
Allegheny Technologies Incorporated*
Applied Systems and Technology Transfer (AST2)*
Arkema, Inc.
ASM International
Association of Manufacturing Technology*
Bayer Material Science*
The Boeing Company
Carnegie Mellon University*
Case Western Reserve University*
Catalyst Connection*
Concurrent Technologies Corporation*
Deformation Control Technology, Inc.
DSM Functional Materials
Energy Industries of Ohio*
EWI
The ExOne Company*
General Electric Company (GE)*
General Dynamics Ordnance and Tactical Systems
Hoeganaes Corporation
Illinois Tool Works, Inc.
Johnson Controls, Inc.*
Kennametal*
Kent Display*
Lehigh University*
The Lincoln Electric Company
Lockheed Martin*
Lorain County Community College
M-7 Technologies*
MAGNET*
Materion Corporation
MAYA Design Inc.
Michigan Technological University
Missouri University of S&T
MIT Lincoln Laboratory
Moog, Inc.
NorTech*
North Carolina State University
Northern Illinois Research Foundation
Northrop Grumman*
Ohio Aerospace Institute*
Optomec*
Pennsylvania State University*
PTC ALLIANCE
Raytheon Company*
RhineStahl Corporation
Robert C. Byrd Institute (RCBI)*
Robert Morris University*
RP+M
RTI International Metals, Inc. *
SABIC
Sciaky, Inc.
SME*
Solid Concepts
South Dakota School of Mines & Technology
Stony Creek Labs
Stratasys, Inc.
Strategic Marketing Innovations, Inc.
Stratonics*
TechSolve*
Texas A&M University*
The Timken Company*
Tobyhanna Army Depot
United Technologies Research Center
University of Akron*
University of California, Irvine
University of Connecticut
University of Dayton Research Institute University of Louisville
University of Maryland – College Park
University of Michigan Library
University of Pittsburgh*
University of Texas – Austin
University of Texas at El Paso
University of Toledo
USA Science and Engineering Festival
Venture Plastics, Inc.
Westmoreland County Community College*
West Virginia University
Wohlers Associates, Inc.*
Wright State University
Youngstown Business Incubator*
Youngstown State University*
Zimmer, Inc.*

Lead Members listed in RED($200K)
Full Members listed in BLUE ($50K)
Supporting Members in BLACK ($15K)
* Original Members (39)
America Makes and ANSI Launch Additive Manufacturing Standardization Collaborative (AMSC); Phase 1 Kick-off Meeting held March 31, 2016

- **5 Working Groups** established to cover AM standards areas

1. **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

2. **Qualification & Certification (Q&C) WG**
   - Meets: Every other Monday, 2:30 – 4 pm Eastern, beginning May 9, 2016

   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).

   Ensure that AMSC WGs have adequate representation from industry & government.

   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.
America Makes & ANSI AMSC Working Groups

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

<table>
<thead>
<tr>
<th>Precursor Materials SG</th>
<th>Process Control SG</th>
<th>Post-Processing SG</th>
<th>Finished Material Properties SG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meets: Every other Tuesday, 1-2 pm Eastern, beginning May 3, 2016 Leader: Jim Adams, MPIF; Justin Whiting, NIST</td>
<td>Meets: Every other Thursday, 1-2 pm Eastern, beginning May 5, 2016 Leader: Justin Whiting, NIST</td>
<td>Meets: Every other Tuesday, 1-2 pm Eastern, beginning May 10, 2016 Leader: Patrick Ryan, LS Management</td>
<td>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</td>
</tr>
<tr>
<td>Chemistry</td>
<td>Digital format (CAD, CAM, machine software)</td>
<td>Heat Treat</td>
<td>Mechanical properties</td>
</tr>
<tr>
<td>Cleanliness</td>
<td>Machine calibration / preventative maintenance</td>
<td>HIP</td>
<td>Quality control</td>
</tr>
<tr>
<td>Feed stock</td>
<td>Machine qualification</td>
<td>Surface finishing</td>
<td>Component testing</td>
</tr>
<tr>
<td>characterization</td>
<td>Machine re-start after maintenance</td>
<td>Machining</td>
<td>Component certification</td>
</tr>
<tr>
<td>Safety &amp; Training</td>
<td>Operator training</td>
<td>Removal of Support Material</td>
<td>Bio-compatibility</td>
</tr>
<tr>
<td>OEM process &amp; control</td>
<td>Parameter control</td>
<td></td>
<td>Chemistry</td>
</tr>
<tr>
<td></td>
<td>Powder handling / blending / use</td>
<td></td>
<td>Design allowsables</td>
</tr>
<tr>
<td></td>
<td>Powder flow monitoring</td>
<td></td>
<td>Cleanliness</td>
</tr>
<tr>
<td></td>
<td>Powder reuse/recycle</td>
<td></td>
<td>Microstructure</td>
</tr>
<tr>
<td></td>
<td>Safety</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• 5 Working Groups established to cover AM standards areas

### 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
• 181 members (June 2016)
• Phase 1 roadmap was published in February 2017 (202 pp.)
• 89 standards gaps identified
  - 5 nondestructive evaluation gaps
  - 15 qualification and certification gaps
  - 7 precursor materials gaps
  - 17 process control gaps
  - 6 post-processing gaps
  - 5 finished materials gaps
  - 26 design gaps
  - 8 maintenance gaps
• Gaps were ranked low (19), medium (51), or high (19) priority depending on criticality, achievability, scope, and effect.
• Future meetings between Standards Development Organizations will discuss how the standards are divvied up.
• Phase 2 currently in progress (Medical and Polymer WGs added).
• Since Fall 2017, WGs have been meeting biweekly.
Contact Jim McCabe of ANSI if interested in participating.

AMSC Sign-up Sheet

• Contact Jim McCabe of ANSI if interested in participating.

America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)
Phase 2 Working Group (WG) Sign-Up Sheet (updated 9/25/17)

Please sign me up for the WGs below
(check all that apply)

Working Groups
Design WG ,
Precursor Materials WG
Process Control WG ,
Post-processing WG
Finished Material Properties WG
Qualification & Certification WG ,
Nondestructive Evaluation WG ,
Maintenance WG
Polymers WG [if you sign up for this WG, you do not need to sign up for the WGs above unless you also have an interest in metals AM standardization]
Medical WG [if you sign up for this WG, you do not need to sign up for any of the WGs above]

Please indicate your sector below
(chose the one that most aligns with your interest)

Industry Sector
Aerospace/Defense
Medical
Ground Vehicle/Heavy Equipment
Energy
Industrial & Commercial Machinery
Electronics

Please provide your contact details below.

Name: Jess. M. Waller
Title: Materials Scientist
Organization: NASA White Sands Test Facility HXS
Address: 11600 NASA Rd., MS 200 LD
Phone: 575-524-5249
Email: jess.m.waller@nasa.gov
Web address: NA

Please email the completed sign-up sheet and your contact details to amsc@ansi.org
AMSC Prioritization Matrix

Criteria (Make the C-A-S-E for the Priority Level)

Criticality (Safety/Quality Implications) - How important is the project? How urgently is a standard or guidance needed? What would be the consequences if the project were not completed or undertaken? A high score means the project is more critical.

Achievability (Time to Complete) - Does it make sense to do this project now, especially when considered in relation to other projects? Is the project already underway or is it a new project? A high score means there's a good probability of completing the project soon.

Scope (Investment of Resources) - Will the project require a significant investment of time/work/money? Can it be completed with the information/tools/resources currently available? Is pre-standardization research required? A high score means the project can be completed without a significant additional investment of resources.

Effect (Return on Investment) - What impact will the completed project have on the AM industry? A high score means there are significant gains for the industry by completing the project.

Score Rankings
Low Priority (a score of 4-6)
Medium Priority (a score of 7-9)
High Priority (a score of 10-12)

Scoring Values
3 - critical; 2 - somewhat critical; 1 - not critical
3 - project near completion; 2 - project underway; 1 - new project
3 - low resource requirement; 2 - medium resource requirement; 1 - resource intensive
3 - high return; 2 - medium return; 1 - low return
Led by Patrick Howard, GE Aviation

28 Members included Aerospace, Automotive and Medical Industries

Mapping Started May 2016 – September 2016
  – One face-to-face meeting

Met bi-weekly – Web meeting

Hosted by ANSI

Identified 6 Standardization Gaps initially
  • 3 gaps being addressed
  • 2 gaps not started
  • 1 gap (in-situ monitoring) moved to Process Control subgroup
Gaps Identified by NDE Working Group

- Gap NDE1: * Terminology for AM Flaws Detectable by NDE Methods
- Gap NDE2: Design and Manufacture of Artifacts or Phantoms to Demonstrate NDE Capability
- Gap NDE3: * Guide for the Application of NDE to Objects Produced by AM Processes
- Gap NDE4: Dimensional Metrology of Internal Features
- Gap NDE5: Data Fusion

- Gap D18: New Dimensioning and Tolerancing Requirements
  - in progress
  - related
  - * = high priority
- Gap D22: In-Process Monitoring
  - In-Situ Monitoring standard moved to AMSC Process Control SG

F42 action
F42 - WK56649
E07 - WK47031

E07 WK authorized
Gaps Identified by NDE Working Group

**Gap NDE1: Terminology for the Identification of AM Flaws Detectable by NDE Methods.** An industry driven standard needs to be developed, with input from experts in metallurgy, NDE, and additive manufacturing fabrication, to identify flaws or flaw concentrations with the potential to jeopardize an AM object’s intended use. Many flaws have been identified but more effort is needed to agree on flaws terminology, providing appropriate names and descriptions. **Recommendation:** Develop standardized terminology to identify and describe flaws, and typical locations in a build. **Priority:** High  
**Custodians:** ISO/ASTM

**Gap NDE2: Standard for the Design and Manufacture of Artifacts or Phantoms Appropriate for Demonstrating NDE Capability.** No published standards exist for the design or manufacture of artifacts or phantoms applicable to calibrating NDE equipment or demonstrating detection of naturally occurring flaws (lack of fusion, porosity, etc.), or intentionally added features (watermarks, embedded geometrical features, etc.). This standard should identify the naturally occurring flaws and intentional features. This standard should also include recommendations regarding the use of existing subtractive machined calibration standards or AM representative artifacts or phantoms. **Recommendation:** Complete work on ASTM WK56649 now proceeding as ISO/TC 261/ASTM F42 JG60, to establish flaw types and conditions/parameters to recreate flaws using AM processes. **Priority:** Medium  
**Custodians:** ISO/ASTM

**Gap NDE3: Standard Guide for the Application of NDE to Objects Produced by AM Processes.** Need an industry-driven standard led by NDE experts and supported by the AM community to assess current inspection practices and provide an introduction to NDE inspection requirements. **Recommendation:** Complete work on ASTM WK47031 and ISO/ASTM JG59. **Priority:** High  
**Custodians:** ISO/ASTM
Gaps Identified by NDE Working Group

Gap NDE4: Dimensional Metrology of Internal Features. Standards are needed for the dimensional measurement of internal features in AM parts. 
*Recommendation*: ASTM F42 and E07 should identify and address additive manufacturing related areas for alignment with current computed tomography dimensional measurement capabilities.
*Priority*: Medium
*Custodians*: ASTM

Gap NDE5: Data Fusion. Since multiple sources and results are combined in data fusion, there is a possible issue of a non-linear data combination that can produce results that can be influenced by the user. Additionally, data fusion may employ statistical techniques that can also introduce some ambiguity in the results. While likely more accurate than non-data fusion techniques, introduction of multiple variables can be problematic. Data fusion techniques also require a certain level of expertise by the user and therefore there might be a need for user certification.
*Recommendation*: The following are needed to address the gap:
- Specific industry standards are needed for data fusion in AM NDE techniques
- Expert education, training, and certification for AM data fusion in NDE
*Priority*: Medium
*Custodians*: ASTM
High Priority Gaps Identified by Qualification & Certification Working Group

**Gap QC1: Harmonization of AM Q&C Terminology.** One of the challenges in discussing qualification and certification in AM is the ambiguity of the terms qualification, certification, verification, and validation, and how these terms are used by different industrial sectors when describing Q&C of materials, parts, processes, personnel, and equipment.
*Custodians: ISO/ASTM, SAE, ASME*

**Gap QC2: Qualification Standards by Part Categories.** A standard classification of parts is needed, such as those described in the Lockheed Martin AM supplier quality checklist and the NASA Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware. This is a gap for the aerospace and defense industries.
*Custodians: NASA, Lockheed Martin, SAE, ISO/ASTM*

**Gap QC4: DoD Source (i.e., Vendor) Approval Process for AM Produced Parts.** As multiple methods of AM continue to mature, and new AM techniques are introduced, end users will need to understand the ramifications of each of these techniques, of what they are capable, and how certain AM procedures might lend themselves to some classes of parts and not others. High pressures, temperatures, and other contained environments could impact the performance or life of safety-critical parts in ways that are not understood. Today, more research is required to determine the delta between traditional and AM methods, starting with the most mature technologies, such as L-PBF.
*Custodians: Service SYSCOMS, Industry, ASME, ISO/ASTM, SAE*

**Gap QC9: Personnel Training for Image Data Set Processing.** Currently, there are only limited qualification or certification programs (some are in process of formation) available for training personnel who are handling imaging data and preparing for AM printing. Develop certification programs for describing the requisite skills, qualification, and certification of personnel responsible for handling imaging data and preparing for printing. The SME organization currently has a program in development.
*Custodians: SME, RSNA, ASTM*

**Gap QC10: Verification of 3D Model.** There are currently no standards for the final verification of a 3D model before it is approved for AM for the intended purpose (e.g., surgical planning vs. implantation; cranial replacement piece; cutting guides which have a low tolerance for anatomical discrepancy).
*Custodians: ASTM, NEMA/MITA, AAMI, ASME, ISO*
Current and future NDE of AM standards under development (ASTM)

**E07**

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

**F42**

- Standard Guide for Intentionally Seeding Flaws in Additively Manufactured Parts
  - POC: S. James

**E07**

- Standard Guide for In-situ Monitoring During the Build of Metal Additive Manufactured Parts Used in Aerospace Applications
  - POC: S. Singh

**E07**

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

**E07**

- Standard Practice for the Design and Manufacture of Artifacts or Phantoms Appropriate for Demonstrating NDE Capability in Additively Manufactured Parts
  - POC: TBD

Balloting begun (CT, ET, MET, PCRT, PT, RT, TT, and UT)

Draft prepared, F42 balloting planned

Motion to register as a formal work item in E07.10 (IR, LUT, VIS, acoustic microscopy)

Future

Future, phys ref stds to demonstrate NDE capability
In-process monitoring/optimization
Post-manufacturing inspection
Receiving inspection
- Guide for Nondestructive Testing of Metal Aerospace Additively Manufactured Parts After Build (POC: Jess Waller/NASA)
- New Guide for In-situ Monitoring of Metal Aerospace Additively Manufactured Parts (POC: Surendra Singh/Honeywell)
NDE of Additively Manufactured Aerospace Parts

ASTM E07.10 Task Group on NDT of Aerospace Materials Standards

Additively Manufactured Parts

ASTM E07-F42
NDT of AM Standards

ASTM E07-F42
New Guide for Nondestructive Testing of Additive Manufactured Parts Used in Aerospace Applications

New Guide for Intentionally Seeding Flaws in Additively Manufactured (AM) Parts

New Guide for Conducting Round Robin Studies for Additive Manufacturing

ISO TC 261
E.U. AM Standards

ASTM F42
U.S. AM Standards

Existing Standards
- Terminology (52921, F2792)
- Reporting Data (F2971)
- Mechanical Properties (F3122)
- Manufacturing File Formats (52915)
- Ti 6-4 Specs (F2924, F3001)
- Metal Powder (F3049)
- UNS N07718 and N06625 Specs (F3055, F3056)
- Plastic Powder Bed Fusion (PBF) (F3091)

New Standards
- Powder Flow Properties
- Anisotropy Effects
- Design for AM
- AMF Support
- Directed Energy Deposition of Metals
- Metal PBF
- UNS S31603 PBF Spec
- UNS S17400 PBF Spec
- UNS S15500 PBF Spec

Seeded Flaws

Round Robin Tests

Adopt E07 Standards

Adopt F42 Standards

Destructive Test
JG51: Terminology
JG52: Standard Test Artifacts
JG53: Requirements for Purchased AM Parts
JG54: Design Guidelines
JG56: Standard Practice for Metal Powder Bed Fusion to Meet Rigid Quality Requirements
JG57: Specific Design Guidelines on Powder Bed Fusion
JG58: Qualification, Quality Assurance and Post Processing of Powder Bed Fusion Metallic Parts
JG59: NDT for AM Parts
JG60: Guide for Intentionally Seeding Flaws in Additively Manufactured (AM)
JG61: Guide for Anisotropy Effects in Mechanical Properties of AM Parts
JG64: Specification for AMF Support for Solid Modeling: Voxel Information, Constructive Solid Geometry Representations and Solid Texturing
JG65: Specification for Additive Manufacturing Stainless Steel Alloy with Powder Bed Fusion
JG66: Technical Specification on Metal Powders
JG67: Design of Functionally Graded Materials
JG68: Additive Manufacturing Safety
Gaps Identified by NDE Working Group

Gaps in progress:

* = high priority

Gap D18: New Dimensioning and Tolerancing Requirements

Gap NDE1: * Terminology for AM Flaws Detectable by NDE Methods

Gap NDE2: Design and Manufacture of Artifacts or Phantoms to Demonstrate NDE Capability

Gap NDE3: * Guide for the Application of NDE to Objects Produced by AM Processes

Gap NDE4: Dimensional Metrology of Internal Features

Gap NDE5: Data Fusion

F42 action

F42 - WK56649

E07 – WK47031

Gap D22: In-Process Monitoring

Related

In-Situ Monitoring standard moved to AMSC Process Control SG

E07 WK authorized
AMSC Gap NDE1: Proposed Terminology for AM Defects

Proposed Terminology:

- Request made to ASTM for an editorial comparison of defect terms already in use.
- Goal is to use terminology that already exists as much as possible to save time and effort.
- Analogous terminology in other standard in development will be coordinated
  - ISO NDE of AM Standard (Dutton), ASTM WK47031 (Waller), and ASTM WK 56649 (James) will be coordinated until inclusion in ASTM/ISO 52900)
- ASTM F42 and ISO TC 261 will include these terms eventually in ASTM/ISO 52900 (AM Terminology Standard)
- ASTM F42 Work Item WK56649 (Technical Contact: Steve James)

- In ASTM F42 review
- Discussed at the ASTM F42/ISO TC 261 meeting in September
- Plans are in work to initiate balloting in F42 this year
ASTM WK47031

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

Developed by Subcommittee: E0710 | Committee E07 | Contact Staff Manager

WK47031

1. Scope

1.1 This Guide discussed the use of established and emerging nondestructive testing (NDT) procedures used during the life cycle of additive manufactured metal parts. 1.2 The parts covered by this Guide are used in aerospace applications; therefore, the inspection requirements for discontinuities and inspection points will in general be different and more stringent than for vessels used in non-aerospace applications. 1.3 The metals under consideration include but are not limited to ones made from aluminum alloys, titanium alloys (Ti-6Al-4V), nickel-based alloys, cobalt-chromium alloys, and stainless steels. NOTE The combustion and ignition properties of finished part need to be taken into account for safe use in aerospace applications. 1.4 Protocols for controlling input materials, and established processes and post-process methods are cited whenever possible. The processes under consideration include but are not limited to Electron Beam Free From Fabrication (EBF3), electron beam melting (EBM), Direct Metal Laser Sintering (DMLS), and Selective Laser Melting (SLM). 1.5 This Guide does not establish or recommend procedures for NDT of additive manufactured metal parts made in

https://www.astm.org/WorkItems/WK47031.htm
79 current members

NASA, ESA, JAXA, NIST, USAF, GE Aviation, Aerojet Rocketdyne, Lockheed, Honeywell, Boeing, ULA and various AM and NDE community participants (including A-Scan Labs, ATI Metals, CTC, Honeywell, Jentek Sensors, Lickenbrock, Magnaflux, Mitre, NSI, Optech Ventures, Southern Research, and Vibrant NDT)
1 negative/4 comments from May balloting resolved/incorporated
ECT section added
Re-balloted 7/14/27, closing date 8/14/17
• Status on ISO TC 261 JG 59 standard for NDT of AM products
  Draft WK47031
  ASTM E07.10 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
• WK47031 references U.S. standards; NP52905 references ISO standards
Designation: X XXXX-XX

Work Item Number: 47031
Date: July 11, 2017

Standard Guide for Nondestructive Testing of Metal Additively Manufactured Aerospace Parts After Build

This standard is issued under the fixed designation X XXXX; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This Guide discusses the use of established and emerging nondestructive testing (NDT) procedures used to inspect metal parts made by additive manufacturing (AM).

1.2 The NDT procedures covered produce data related to and affected by microstructure, part geometry, part complexity, surface finish, and the different AM processes used.

1.3 The parts tested by the procedures covered in this Guide are used in aerospace applications; therefore, the inspection requirements for discontinuities and inspection points in general are different and more stringent than for materials and components used in nonaerospace applications.

1.4 The metal materials under consideration include but are not limited to aluminum alloys, titanium alloys, nickel-based alloys, cobalt-chromium alloys, and stainless steels.

1.5 The manufacturing processes considered use powder and wire feedstock, and laser or electron energy sources. Specific powder bed fusion (PBF) and directed energy deposition (DED) processes are discussed.

• Focuses on metal AM aerospace parts made by DED and PBF processes.
1.6 This Guide does not establish or recommend procedures for NDT of additively manufactured metal parts made in space under conditions of zero gravity.

1.7 This Guide discusses NDT of parts after they have been fabricated. Parts will exist in one of two possible states: either as 1) raw, as-built parts before post-processing (heat treating, hot isostatic pressing, machining, etc.), 2) finished parts after all post-processing is completed. In-situ monitoring procedures used during the build process are not covered by this Guide.

NOTE—Post-processing can alter defect size and distribution in a part, thus altering the probability of detection (POD) of a given defect by NDT. For this reason, NDT before and after post-processing is recommended to determine if defects are eliminated or introduced by post-processing, or to screen raw, as-built parts before performing labor intensive post-processing steps.

1.8 The NDT procedures discussed in this Guide are used by cognizant engineering organizations to detect and characterize flaws and defects produced by processing and postprocessing. The post-process NDT procedures are used to detect both surface and volumetric flaws in as-built (raw) or post-processed (finished) parts.

1.9 The NDT procedures discussed in this Guide are computed tomography (CT, Section 7, including microfocus CT), eddy current testing (ECT, Section 8), optical metrology (MET, Section 9), penetrant testing (PT, Section 10), process compensated resonance testing (PCRT, Section 11), radiographic testing (RT, Section 12), thermographic testing (TT, Section 13), and ultrasonic testing (UT, Section 14).

1.10 Other NDT procedures such as leak testing (LT) and magnetic particle testing (MT), which have known utility for inspection of AM parts, are not covered in this Guide.

- Focuses on NDE of AM parts after build, not in-situ monitoring.
- Covers CT, ET, MET, PT, PCRT, RT, TT, and UT, but not LT or MT.
## FIG. 4.3 Common additive manufacturing processes

4.5 *Processes*—The AM processes covered in this Guide are differentiated by input material (powder or wire) and energy source (electron, laser or plasma) (Figure 4.3). Plasma energy sources (typically GTA (gas tungsten arc), PA (plasma arc), PTA (plasma transferred arc), and GMA (gas metal arc) used in DED are not discussed in this Guide. For purposes of this Guide the AM processes are defined by ISO/ASTM 52900 and are subdivided into two additive manufacturing process categories: 1) PBF, and 2) DED. For a discussion of the relative merits of the PBF and DED processes according to build volume, detail resolution, deposition rate, power efficiency, coupling efficiency, and cleanliness, consult Guide F3187. For details on DED feedstock, processing equipment (machine preparation, conditioning, calibration, and monitoring), atmospheric control, post-processing, safety, manufacturing plan, and process specification, also consult Guide F3187.

Note—Other AM processes; namely, vat photopolymerization, material jetting, binder jetting, materials extrusion, and sheet lamination covered in ISO 17296-2, or relying on other energy sources such as chemical reaction or plasma arcs are not considered in this Guide.
### TABLE 4.2 Additive Manufacturing Defect Classes and Subclasses

<table>
<thead>
<tr>
<th>Defect Class</th>
<th>Defect Subclass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>roughness, underfill, powder shorting, overfill, crater, stair stepping, meet surface spec</td>
</tr>
<tr>
<td>Porosity</td>
<td>spherical gas porosity, microporosity, void, surface breaking</td>
</tr>
<tr>
<td>Cracking</td>
<td>hot cracking, cold cracking, crater, cracking, HAZ as in DED to substrate, tearing</td>
</tr>
<tr>
<td>Lack of Fusion</td>
<td>cold lap, trapped powder, oxide lap, linear, planar, post HIP</td>
</tr>
<tr>
<td>Part Dimensions</td>
<td>external, internal, lattice, custom</td>
</tr>
<tr>
<td>Density</td>
<td>density, weight, volume, meets partial density spec</td>
</tr>
<tr>
<td>Inclusions</td>
<td>inclusions, segregation, banding, planar</td>
</tr>
<tr>
<td>Discoloration</td>
<td>oxidation, other</td>
</tr>
<tr>
<td>Residual Stress</td>
<td></td>
</tr>
<tr>
<td>Hermetic Sealing</td>
<td>vacuum, pressure</td>
</tr>
</tbody>
</table>

---

- Lists what are considered to be the major AM defect Classes and Subclasses.

---

Footnote: [4] Abbreviations used: --- = not applicable, DED = Directed Energy Deposition, HAZ = Heat Affected Zone, HIP = Hot Isostatic Pressing
### TABLE 4.1 Nondestructive Test Detection of Typical Additive Manufacturing Flaws \(^a^, \(^b^\)

<table>
<thead>
<tr>
<th>Flaw/Artifact(^c^)</th>
<th>Observed in PBF or DED?</th>
<th>Why?</th>
<th>Post-Process Detection</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>both</td>
<td>Poor selection of parameters, moisture or contamination of feed material or process environment, inadequate handling, storage, vaporization of minor alloying constituents depending on material feedstock. Errors in precision of beam delivery.</td>
<td>Depending on sample geometry and size of porosity may be detected using CT/ECT/PCRT/RT/UT</td>
<td>HIP recoverable (may not be full)</td>
</tr>
<tr>
<td>Voids</td>
<td>both</td>
<td>Powder run out, changes in the energy density of the impinging beam creating keyhole melting or vaporization conditions that entrap voids or create spatter (spherical molten ejecta) leaving holes, and voids that may be covered by subsequent layers of fused materials. System drift or calibration issues may come into play to create conditions of LOF. Bridging of powder in the hopper / poor flow properties.</td>
<td>Depending on sample geometry and size of voids may be detected using CT/ECT/PCRT/RT/UT</td>
<td>HIP recoverable depending on size (not be fully recoverable regardless)</td>
</tr>
<tr>
<td>Layer defects</td>
<td>Unique to AM(^f^)</td>
<td>Interruption to powder supply, optics systems errors (laser) or errors in data. Contamination of build environment purity (inert gas interruption or other process interruption such as changing the filament emitter within and electron beam gun. Powder supply blending or mixing between one batch and another, a new lot of filler wire, etc.</td>
<td>Depending on sample geometry and size of flaw may be detected using CT/ECT/PCRT/RT/UT</td>
<td>HIP recoverable depending on size (not be fully recoverable regardless)</td>
</tr>
<tr>
<td>Cross-layer defects</td>
<td>Unique to AM(^f^)</td>
<td>Poor selection of parameters, contamination or degradation of the processing environment. Discoloration (for example DED-PA of Ti alloys) as detected visually can indicate a process out of control. Error in the precision of the beam delivery.</td>
<td>Depending on sample geometry and size of flaw may be detected using CT/ECT/PCRT/RT/UT</td>
<td>HIP recoverable depending on size (not be fully recoverable regardless)</td>
</tr>
<tr>
<td>Under melted material/unconsolidated powder (LOF)</td>
<td>both</td>
<td>Poor selection of parameters, poorly developed and controlled process or a process out of control creating a poorly resolved flaw state. Errors in the precision of beam delivery.</td>
<td>Most probably CT, and PCRT, detectability depends on sample geometry and size PCRT</td>
<td>Only fixable during the process</td>
</tr>
<tr>
<td>Cracking(^d^)</td>
<td>Unique to AM(^f^)</td>
<td>AM PBF failure to completely clean one alloy powder from the build environment prior to processing another, DED</td>
<td>Depending on sample geometry and size of crack may be</td>
<td></td>
</tr>
</tbody>
</table>

- Links defect with probable process cause and recoverability by post-processing, and applicable NDE methods.
Links defect class with applicable NDE methods covered and not covered by the Guide.

---

| Defect Class       | CT/RT/CR/DR | ECT | MET | PCRT | PT | TT | UT | AE | LT | ND | MT | VT |
|--------------------|-------------|-----|-----|------|----|----|----|----|----|----|----|----|----|
| Surface            | X<sup>C</sup> | X<sup>D</sup> | X   | ...  | X<sup>D</sup> | ... | ... |    |    |    |    | X  |
| Porosity           | X           | X<sup>D</sup> | ...  | X    | X<sup>D</sup> | ... | X   |    |    |    |    |    |
| Cracking           | X           | X<sup>D</sup> | ...  | X    | X<sup>D</sup> | X   | X   |    |    |    |    |    |
| Lack of Fusion     | X           | X<sup>D</sup> | ...  | X    | X<sup>D</sup> | X   | X   |    |    |    |    |    |
| Part Dimensions    | X           | ...  | X   | ...  | ... | ... |    |    |    |    |    |    |
| Density<sup>G</sup> | X<sup>H</sup> | ...  | ... | ...  | ... | ... |    |    |    |    |    |    |
| Inclusions         | X<sup>I</sup> | X<sup>D</sup> | ...  | ... | X<sup>D</sup> | X<sup>G</sup> | X<sup>E</sup> |    |    |    |    |    |
| Discoloration      | ...         | ...  | ... | ...  | ... | ... |    |    |    |    |    |    |
| Residual Stress    | ...         | X<sup>D</sup><sub>J</sub> | ...  | ... | ... | ... | ... | X<sup>E</sup> |    |    |    |    |
| Hermetic Sealing   | ...         | ...  | ... | ...  | ... | ... | ... | ... | X<sup>E</sup> |    |    |    |


<sup>B</sup> Includes Digital Imaging.

<sup>C</sup> Especially helpful when characterizing internal passageways or cavities (complex geometry parts) for underfill and overfill, or other internal feature not accessible to MET, PT or VT (including borescopy).

<sup>D</sup> Applicable if on surface.

<sup>E</sup> Macroscopic cracks only.

<sup>F</sup> If large enough to cause a leak or pressure drop across the part.

<sup>G</sup> Pycnometry (Archimedes principle).

<sup>H</sup> Density variations will only show up imaged regions having equivalent thickness.

<sup>I</sup> If inclusions are large enough and sufficient scattering contrast exists.

<sup>J</sup> Residual stress can be assessed if resulting from surface post-processing (for example, peening).
17-03 E07.10 subcommittee ballot results closing 8/14/17
- 1 Negative
- 7 Comments

Next balloting cycle planned for February-March.
• Telecon held 12/19/17
• Draft available
• Writing teams established
  1) Sensor selection (address sensors for different techniques 3-6 below)
     a. Surendra Singh (lead)
     b. Prabir Chaudhury/Exova
  2) Draft new content for IR melt pool monitoring (NIST, group)
     a. Brandon Lane (lead)/NIST
     b. Jarred Heigel/NIST
     c. Prabir Chaudhury/Exova
     d. Eric Burke/NASA LaRC
     e. Ibo Matthews/LLNL
  3) Section on Visible and Spectroscopic characterization (Middendorf)
     a. John Middendorf (lead)/UTC Dayton
     b. Greg Loughnane/UTC Dayton
     c. Dave Maass/Flightware
     d. Anja Loesser/EOS
  4) Finalize LUT section (Klein)
     a. Marvin Klein (lead)/Optech Ventures
     b. Ben Dutton/MTC
  5) Acoustic Microscopy
     a. Surendra Singh (Lead)
     b. Prabir Chaudhury
• Discuss at the ASTM E07.10 TG meeting on 1/22/18 at 11 a.m. EST
Fabricate AM physical reference samples to demonstrate NDE capability
• Develop a defects catalogue
• Develop in-process NDE to improve feedback control, maximize part quality and consistency, and obtain ready-for-use parts
• Develop post-process NDE of finished 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)
Demonstrate NDE capability

RT & PCRT Sample

<table>
<thead>
<tr>
<th>Artifact</th>
<th>Lack of Fusion</th>
<th>Depth</th>
<th>Length</th>
<th>Orientation to build direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOF 1</td>
<td>1% of Thickness or 1 layer x 1/4 t</td>
<td>.25&quot; (6.35mm)</td>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>LOF 2</td>
<td>2% of Thickness or 2 layers x 1/4 t</td>
<td>.25&quot; (6.35mm)</td>
<td>45°</td>
<td></td>
</tr>
<tr>
<td>LOF 3</td>
<td>3% of Thickness or 3 layers x 1/4 t</td>
<td>.25&quot; (6.35mm)</td>
<td>90°</td>
<td></td>
</tr>
<tr>
<td>LOF 4</td>
<td>4% of Thickness or 4 layers x 1/4 t</td>
<td>.25&quot; (6.35mm)</td>
<td>0°</td>
<td></td>
</tr>
</tbody>
</table>

ECT Sample

Reference: ASTM E 1320 “Standard Reference Radiographs for Titanium Castings”

Multiuse Sample (MUS)

<table>
<thead>
<tr>
<th>Artifact</th>
<th>Lack of Fusion</th>
<th>Diameter</th>
<th>Orientation to build direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOF 1</td>
<td>1% of Thickness or 1 layer x 1/4 t</td>
<td>.060&quot;</td>
<td>0°</td>
</tr>
<tr>
<td>LOF 2</td>
<td>2% of Thickness or 2 layers x 1/4 t</td>
<td>.060&quot;</td>
<td>0°</td>
</tr>
<tr>
<td>LOF 3</td>
<td>3% of Thickness or 3 layers x 1/4 t</td>
<td>.060&quot;</td>
<td>0°</td>
</tr>
<tr>
<td>LOF 4</td>
<td>4% of Thickness or 4 layers x 1/4 t</td>
<td>.060&quot;</td>
<td>0°</td>
</tr>
</tbody>
</table>

UT Sample

Stepped vs. One Thickness

<table>
<thead>
<tr>
<th>Artifact</th>
<th>Diameter</th>
<th>Orientation to build direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOF 1</td>
<td>.050&quot;</td>
<td>0°</td>
</tr>
<tr>
<td>LOF 2</td>
<td>.050&quot;</td>
<td>0°</td>
</tr>
<tr>
<td>LOF 3</td>
<td>.050&quot;</td>
<td>0°</td>
</tr>
<tr>
<td>LOF 4</td>
<td>.050&quot;</td>
<td>0°</td>
</tr>
</tbody>
</table>

PT Sample

Fatigue Crack or Surface Texture

An AM panel has an EDM notched placed on one side, which is cycled to grow a through-crack for evaluation on the side opposite the notch, allowing evaluation of a tight crack on an as-built surface or the development/technical review of penetrant removal (high background issue).
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>DMLS</td>
<td>DMLS (metal), LS (plastic)</td>
<td>LS</td>
<td>EBF³</td>
<td>EBM</td>
</tr>
<tr>
<td><strong>alloys</strong></td>
<td>titanium, Inconel, and aluminum</td>
<td>titanium, SS PH1, vero-white RGD835</td>
<td>SS</td>
<td>titanium</td>
<td>titanium</td>
</tr>
<tr>
<td><strong>reference standard geometries</strong></td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" 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 matl, (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 ? MeV CT</td>
<td>post-process ? 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>
Trapped powder defect standards (ongoing NASA MSFC effort)
Inconel® insert and sleeves fabricated in early 2016 and distributed to participants with CT capability.
ASTM WK47031 Effort: CT of Concept Laser Samples in North America

CT Round Robin Testing (Previously Evaluated)

**Europe**: The Fraunhofer Development Center X-ray Technology, Yxlon, GE

**Japan**: JAXA

Planned Evaluation (12)

**N America**: NASA MSFC, LMCO, Pratt & Whitnet/UTC, NASA GSFC, Boeing (two locations), GE Aviation, JHUAPL, Yxlon, UTAS, EWI, Vibrant EWI

Preplanning – Participation Rules
- Samples will be shipped as one set
- Two Week loan period
- Present findings at WK47031 Link Call
- Provide presentation to WK47031
- Ship to next participant on list

Proposed Schedule

<table>
<thead>
<tr>
<th>Affiliation</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>JHUAPL</td>
<td>7/31 – 8/11</td>
</tr>
<tr>
<td>NASA</td>
<td>8/16 – 8/30</td>
</tr>
<tr>
<td>UTAS</td>
<td>9/4 – 9/15</td>
</tr>
<tr>
<td>PW</td>
<td>9/20 – 10/4</td>
</tr>
<tr>
<td>EWI</td>
<td>10/9 – 10/20</td>
</tr>
<tr>
<td>Boeing</td>
<td>10/25 – 11/8</td>
</tr>
<tr>
<td>NASA</td>
<td>11/13 – 12/1</td>
</tr>
<tr>
<td>AF</td>
<td>12/6 – 12/20</td>
</tr>
<tr>
<td>NSI</td>
<td>1/3 – 1/17</td>
</tr>
</tbody>
</table>

List with addresses will accompany the samples
1. Star artefacts:

- **Star designs are available for**
  - Inconel
  - Ti
  - Al

- Maximum material thickness for XCT scan is shown by red arrows. This is based on 10% transmission on nickel suggested by XCT standard.

- **Defects type:**
  - Horizontal cylinders (layer defect)
  - Vertical cylinders (cross layer defect)
  - Sphere (trapped powder)
  - Cylinders in various orientation (trapped powder)
  - A section containing no defect (reference)
  - Inclusions will be made by introducing a desirable material in a selected cavity
Star artefact design: embedded feature details:

- Horizontal cylinders
  - Fixed 2 mm length.
  - $\varnothing$ (um) = 20, 50, 100, 200, 500, 1000, and 1500.

- Reference section (no defect)

- Cylinder in various orientation
  - Fixed 2 mm length.
  - $\varnothing$ (um) = 200 or 300

- Spheres
  - $\varnothing$ (um) = 20, 50, 100, 200, 500, 1000, and 1500.

- Vertical cylinders
  - Fixed 2 mm length.
  - $\varnothing$ (um) = 20, 50, 100, 200, 500, 1000, and 1500.

These are intentional idealized features to mimic defects (are not natural defects)
In-house CT for Inconel star artefact - horizontal cylinders (simulate layer defects):

**Results:**
- Only the largest 3 are clearly visible (Ø500, Ø1000, and Ø1500 μm)
- Ø200 μm is very faint
- Anything smaller than Ø200 mm is not visible (Ø20, Ø50, and Ø100 μm)
In-house CT of Inconel star artefact – vertical cylinders (simulate cross-layer defects):

Results:
- Only the largest 3 are clearly visible (Ø500, Ø1000, and Ø1500 μm)
- Ø200 μm is very faint
- Anything smaller than Ø200 mm is not visible (Ø20, Ø50, and Ø100 μm)
2. Air foils:

**Material: Inconel**
- Cylindrical (layer defects)
  - Ø100 μm
  - Ø300 μm
  - Ø500 μm
  - Ø700 μm
In-house CT of Inconel air foil - horizontal cylinders inside concave side (layer defects)

Results:
- All 4 defects are visible (Ø100, Ø300, Ø500, and Ø700 μm)
- Ø100 μm is not visible in some locations
- Volunteers sought for Star and air foil artefact NDE
Apply NDE to understand effect-of-defect
• Develop a [defects catalogue](#)
• Develop [in-process NDE](#) to improve feedback control, maximize part quality and consistency, and obtain ready-for-use parts
• Develop [post-process NDE](#) of finished 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)
ASTM E07.10 WK47031 Round Robin Testing Participants

CT/MET, MSFC/J. Walker, R. Beshears
* metal SLM parts, MSFC/K. Morgan, B. West
* ABS plastic parts, MSFC/N. Werkheiser, T. Prater
CT, GSFC/J. Jones
* EBF3 metal parts, LaRC/K. Taminger
POD/NDE of AM, ESA/G. Sinnema, M. Born, L. Pambaguian
CT, JAXA/S. Hori, T. Nakagawa, M. Mitsui, H. Kawashima, A. Kioke
AE, MRI/E. Ginzel
CT/acoustic microscopy, Honeywell/S. Singh
UT/PT, Aerospace Rocketdyne/S. James
CT/RT, USAF/J. Brausch, K. LaCivita
CT, Fraunhofer/C. Kretzer
CT, GE Sensing GmbH/T. Mayer
PCRT, Vibrant Corporation/E. Biedermann
PT, Met-L-Check/M. White
RT, UT, DIC, Southern Research/J. Chambers, M. Parks
NRUS, LANL/M. Remillieux
* Concept Laser/M. Ebert
* DRDC/S. Farrell
† * Airbus/A. Glover
* Incodema3D/A. Krishnan, S. Volk
† * CalRAM/S. Collins
† * UTC/J. Middendorf, G. Loughnane

* delivered or committed to deliver samples
† E8 compliant or tensile sacrificial dogbone samples
μ–CT/CT:

Also utilize capability at GE, Yxlon, JHU APL, JAXA, NASA MSFC, and NASA 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 (NRUS)

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
Approach

Determine effect-of-defect on sacrificial specimens w/ variable process history (left) and embedded artefacts (right):

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

CT at GRC as of November

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
Parallel effort
Determine effect-of-defect on sacrificial specimens w/ different process histories:

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

3. CalRAM Electron Beam PBF samples

Insert 1 “Lower Laser Power”

Insert 4 “Trace Width Bigger”
Coordinated by S. James (Aerojet Rocketdyne)

**Electron Beam Freeform Fabrication (EBF³)**
- NASA LaRC
- Inconel 625 on copper

**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**

**UTC/Southern Research**
- Inconel 718 and Ti-6A-4V dogbones

**Laser-PBF (L-PBF)**
- Incodema3D
  - Al-Si-10Mg cylinders

**Electron Beam-PBF (E-PBF)**
- CalRAM
  - Ti-6Al-4V dogbones

**Characterized to date by various NDE methods (CT, DIC, PT, PCRT, RT, UT)**
Coordinated by S. James (Aerojet Rocketdyne) and J. Waller (NASA WSTF)

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

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

**Electron Beam-PBF (E-PBF)**
Met-L-Check
SS 316 PT/RT panels w/ EDM notches

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

1.9% porosity

5.1% porosity

**Directed Energy Deposition (DED)**
NASA MSFC ABS plastic parts with optimal and off-optimal settings (T. Prater)
Coordinated by B. Dutton (MTC)

Star artefacts (L-PBF)
Inconel, Ti-6Al-4V

Air foil (L-PBF)
Inconel

Star artefact (E-PBF)
Ti-6Al-4V

Aluminum planned
Thomas Meyer, Application Leader Europe for GE Radiography used CT on Concept Laser Inconel® 718 inserts and prisms with different internal features and process histories (cylindrical insert geometry: $h < 50$, $d < 35$ mm)

- Good visibility of all details obtained (structures, pores, defects)
- Automatic pore analysis possible
- Cone and fan beams were used
- Scatter correction used (cone beam)

Cone beam CT (3D) is fast but scattered radiation can affect the image quality. Fan beam CT is not affected by scattered radiation but is slow.
ASTM Round Robin Testing Illustrative Results

explored the use of an inert screening liquid such as perfluorodecalin to reduce beam hardening artifacts, while improving the contrast of internal features:

Computed tomogram of an additively manufactured Ti-6Al-4V capability demonstration specimen acquired under standard imaging conditions showing improved contrast with a screening liquid (middle) versus without (top). **Contrast with screening liquid was quantitatively comparable to a high resolution computed tomogram** of the same specimen imaged in air (bottom) (scale bars = 3.5 mm left) and 8 to 8.5 mm (right))
UT of AM Flanges:

Ultrasonic immersion test image of a flange (top) showing the correlation of areas with **loss of back reflection** with **areas of build layer separation** determined by a volumetric c-scan (bottom).
PT of AM parts:

showed that rough, as built surfaces can entrap (hold) penetrant after washing, creating a background which can mask the indications of interest. Attached powder creates small crevices, which allows for capillary action of the penetrant to occur just as a surface breaking discontinuity would, thus masking the flaw.

Effect of sand grit blasting on PT results: visible images (top), 200× micrographs (middle), and UV images of grit-blasted surfaces with penetrant applied (bottom)
September 2017 Webmeeting Round Robin Sample Activity

statused the group on Process Compensated Resonance Test (PCRT) results on three groups of CalRAM Ti6-4 tensile dogbones made using an EB-PBF process: 1) 10.7-cm nominal dogbones, 2) 13.6-cm nominal dogbones, and 3) 13.6-cm lack of fusion (LOF) group (area of LOF in dog bone gage section).

CalRAM EB-PBF samples (contact: Shane Collins) configured for PCRT (contact: Eric Biedermann)

PASS/FAIL testing using Mahalanobis-Taguchi System (MTS) scores
reported on process-structure-property correlation and low-cost NDE alternatives on nominal and off-nominal AM sacrificial tensile specimens made with two common alloys (Inconel® 718 and Ti-6Al-4V, plus wrought controls). So far, Inconel® (Cluster A) specimens have been machined from rectangular bar stock in two orientations (parallel and perpendicular to the build direction) and characterized by RT, UT, and high temperature Digital Image Correlation (DIC).

high temperature DIC measure Poisson’s ratio, CTE, and modulus
Working drafts of the Standard Guide WK47031, meeting minutes, and round-robin testing activity presentations are posted on-line:

Collaboration Area

Collaboration on WK47031
New Standard Nondestructive Testing of Additive Manufactured Metal Parts Used in Aerospace Applications

November 2016 Webmeeting
June 2016 Webmeeting
May 2016 Webmeeting
February 2016 Webmeeting
January 2016 Webmeeting
December 2015 Webmeeting
October 2015 Webmeeting
September 2015 Webmeeting
August 2015 Webmeeting
Round Robin Testing Information
May 2015 Webmeeting
July 2015 Webmeeting
Qualification & Certification
• Develop a **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
• 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 NASA AM Qualification & Certification Documents (cont.)

- MSFC Technical Standard for Additively Manufactured Spaceflight Hardware
  - Draft 1 - July 7, 2015
  - Released October 18, 2017

- MSFC Technical Standard

- MSFC Technical Standard for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes
Qualification & Certification/NASA MSFC Guidance

**MSFC-STD-3716**

Lists foundational process and part production control requirements:
- Qualified Metallurgical Process
- Equipment Control
- Personnel Training
- Material Property Requirements
- Part Design and Production Control Requirements
- Establishing Material Property Design Values

**MSFC-SPEC-3717**

Contains *procedures* for implementing the foundational requirements in 3716:
- Qualified Metallurgical Process
- Equipment Control
- Personnel Training
National Aeronautics and Space Administration

NASA Engineering and Safety Center Technical Bulletin No. 17-01

Development of NASA Standards for Enabling Certification of Additively Manufactured Parts

There are currently no NASA standards providing specific design and construction requirements for certification of additively manufactured parts. Several international standards organizations are developing standards for additive manufacturing; however, NASA mission schedules preclude the Agency from relying on these organizations to develop standards that are both timely and applicable. NASA and its program partners in manned spacecraft (the Commercial Crew Program, the Space Launch System, and the Orion Multi-Purpose Crew Vehicle) are actively developing additively manufactured parts for flight as early as 2018. To bridge this gap, NASA Marshall Space Flight Center (MSFC) has authored a Center-level standard (MSFC-STD-3716) to establish standard practices for the Laser Powder Bed Fusion (LPBF) process. In its draft form, the MSFC standard has been used as a basis for LPBF process implementation for each of the human spaceflight programs. The development of an Agency-level standard is proposed, based upon the principles of MSFC-STD-3716, which would have application to multiple additive manufacturing processes and be readily adaptable to all NASA programs.

Background

Additive manufacturing (AM) has rapidly become prevalent in aerospace applications. AM offers the ability to rapidly manufacture complex part designs at a reduced cost; however, the extreme pace of AM implementation introduces risks to the safe adoption of this developing technology. The development of aerospace quality standards and specifications is required to properly balance the benefits of AM technologies with the inherent risks. NASA design and construction standards do not yet include specific requirements for controlling the unique aspects of the AM process and resulting hardware. While a significant national effort is now focused on creating standards for AM, the current and scheduled release of these consensus standards do not support the near-term programmatic needs of NASA.

MSFC Standard and Application to Human Spaceflight Hardware

NASA MSFC has led with the development of a Center-level standard, MSFC-STD-3716, to aid in the development of standard practices for LPBF processes. This standard and its companion specification, MSFC-SPEC-3717, provide a consistent framework for the development, production, and evaluation of additively manufactured parts for spaceflight applications. The standard contains requirements addressing material property development, part classification, part process control, part inspection, and acceptance. The companion specification provides requirements for qualification of LPBF metallurgical processes, equipment process control, and personnel training. Engineering from the three active manned spaceflight programs have used the MSFC standard as a guideline for implementation of AM parts, ensuring partners establish reliable AM processes and meet the intent of all NASA standards in material, fracture control, snoopstructure evaluation, and propulsion structures.

Path Forward to an AM Standard

In addition to human spaceflight, standards for appropriate application of AM to other NASA missions such as science and aeronautics require consideration. Full embrace of AM technologies requires standardization beyond the Powder Bed Fusion process. A planned Agency standard applicable to all NASA programs and most AM technologies is currently being explored. Proper standardization is the key to enabling the innovative process of AM, while ensuring safe, functional, and reliable AM parts.

References

1. MSFC STD 3716 “Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals,” 2017

For information contact the MSFC at www.msfc.nasa.gov

Contact: Doug Wells (MSFC)

- Provides a consistent framework for the development, production, and evaluation of AM spaceflight parts.
- 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 and effect-of-defect are still emerging.

§ NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components
Certification is the affirmation by the program, project, or other reviewing authority that the verification and validation process is complete and has adequately assured the design and as-built hardware meet the established requirements to safely and reliably complete the intended mission.

Certification process has two parts:

**Design Certification:**
Design certification is a stand-alone event that typically occurs at the completion of the design process, but prior to use, or following a significant change to the design, understanding of environments, or system behavior.

**As-built Hardware Certification:**
Hardware certification occurs throughout the life-cycle of the hardware to ensure fabricated hardware fully meets the intent of the certified design definition at the time of flight. All hardware in the flight system will have verification of compliance leading to final Certification of Flight Readiness (CoFR).
Overview of MSFC-STD-3716 Standard

Process Controls provide the basis for reliable part design and production

Part Production Controls are typical of aerospace operations and include design, part classification, pre-production and production controls

NDE decisional point
Abbreviations Used in MSFC-STD-3716

AMCP = Additive Manufacturing Control Plan
AMRR = Additive Manufacturing Readiness Review
ECP = Equipment Control Plan (foundational control)
  • Machine qual, re-qual, maintenance, contamination control
MPS = Material Property Suite (foundational control)
  • Actively maintained database of material property values containing “allowables” integrated through PCRDs. Includes material test data, design values, and criteria needed to implement and maintain SPC.
PCRD = Process Control Reference Distribution
  • Defined reference state to judge process consistency
PPP = Part Production Plan
  • Deliverable requiring NASA approval prior to proceeding into production; conveys the full design and production intent of the part
QMP = Qualified Metallurgical Process (foundational control)
  • A range of controls covering powder feedstock, process parameters, post-processing, and final detail and rendering
QMS = Quality Management System
  • Required at AS9100 level with associated audits
QPP = Qualified Part Process
  • Finalized “frozen” part process after a successful AMRR; used to control part production and part integrity
SPC = Statistical Process Control
  • Design criteria obtained from the MPS for witness test evaluation
NASA AM Part Classification A-B-C

Comprehensive NDE required for surface and volumetric defects

- NASA classifications should not 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.
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, consequence of failure, 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.
NASA Class A, B and C subclasses 1-4 arise from variable AM Risk, which accounts for part inspection feasibility and AM build sensitivities:

<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 be fully removed on all fatigue-critical surfaces</strong>?</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 ≥ 1mm 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>
Lockheed AM Part Classification I-II-III

Lockheed determined that the machine and materials process shall be established and repeatable, and that each AM part may require a different level of part acceptance testing (e.g., NDE) based on part category or class.

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I</td>
<td>High – Flight-critical - primary structure</td>
</tr>
<tr>
<td></td>
<td>• Structural, Primary loads, Full Environmental, Safety of Flight</td>
</tr>
<tr>
<td></td>
<td>• Full exposure to operational loads and environment</td>
</tr>
<tr>
<td></td>
<td>• Quality of workmanship inspection Dimensional Analysis of mating and critical surfaces, Form, Fit and Function compatibility</td>
</tr>
<tr>
<td></td>
<td>• Parts <strong>shall</strong> require X-Ray, CT or Laser Scanning, Proof (Tensile) Loading, Micro-Structure, Density, Porosity, Chemistry of First Article part.</td>
</tr>
<tr>
<td></td>
<td>• Thermal, Shock/Vibration, Environmental and Program Specific testing <strong>are</strong> required to validated process and design.</td>
</tr>
<tr>
<td>Class II</td>
<td>Medium – Flight - secondary structure</td>
</tr>
<tr>
<td></td>
<td>• Secondary Structure, Multiple Load Paths, Partial Environment, High Margins</td>
</tr>
<tr>
<td></td>
<td>• Limited exposure to operational loads and environment. Dimensional Analysis may include CM, mating and critical surfaces, Quality of workmanship inspection.</td>
</tr>
<tr>
<td></td>
<td>• Parts <strong>may</strong> require X-Ray, CT or Laser Scanning, Proof (Tensile) Loading, Micro-Structure, Density, Porosity, Chemistry of First Article part.</td>
</tr>
<tr>
<td></td>
<td>• Thermal, Shock/Vibration, Environmental and Program Specific testing <strong>may be</strong> required to validated process and design.</td>
</tr>
<tr>
<td>Class III</td>
<td>Support – Non-structural</td>
</tr>
<tr>
<td></td>
<td>• Limited exposure to environmental conditions</td>
</tr>
<tr>
<td></td>
<td>• Ground station, Lab environment, test equipment</td>
</tr>
<tr>
<td></td>
<td>• Limited Dimensional Analysis: mating and critical surfaces only – Quality of workmanship inspection</td>
</tr>
<tr>
<td>Class I</td>
<td>Low – Non-critical</td>
</tr>
<tr>
<td></td>
<td>• Non-structural, No consequence of failure, No Mission Impact</td>
</tr>
<tr>
<td></td>
<td>• Working prototypes/models</td>
</tr>
<tr>
<td></td>
<td>• Quality of workmanship inspection</td>
</tr>
<tr>
<td>Class I</td>
<td>Prototype/Models</td>
</tr>
<tr>
<td></td>
<td>• Engineering use only</td>
</tr>
<tr>
<td></td>
<td>• Form, Fit, Function, concept parts</td>
</tr>
<tr>
<td></td>
<td>• Visual inspection</td>
</tr>
</tbody>
</table>

137
Purpose of MSFC-STD-3716 Standard

- Since PBF processes have not yet had the benefit of years engineering experience by NASA, its contractors, or third-party OEMs, undiscovered failure modes are likely to remain.
- MSFC-STD-3716 offers a conservative approach to existing NASA requirements by treating AM as an evolving process subject to meticulous production controls, thus minimizing the likelihood and consequences of unintended failure.
- The purpose of MSFC Technical Standard MSFC-STD-3716 is twofold:
  1. Provide a defined system of foundational and part production controls to manage the risk associated with the current state of L-PBF technology.
  2. Provide a consistent set of products the cognizant engineering organization (CEO) and the Agency can use to gauge the risk and adequacy of controls in place for each L-PBF part.
NASA MSFC-STD-3716 implements five aspects of process control for AM:

- Qualified Metallurgical Process (QMP)
- Equipment Control Plan (ECP)
- Training Plan (including control of vendors)
- Part Production Plan (PPP)
- Statistical Process Control (SPC)

- 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 MSFC documents provide a consistent framework for these controls and provides a consistent set of review/audit products.
Early comparisons of Inconel 718 produced by MSFC and by vendors indicated significant variations in mechanical and microstructural properties, which raised concerns about certification of parts produced via additive manufacturing.

Participants used a variety of machine models, providing a diverse array of select laser melting build parameters.

The vendors were provided build files, instructions for metallography specimens, and heat treatment specifications but otherwise allowed to use in house processes.

<table>
<thead>
<tr>
<th>LAB</th>
<th>OEM</th>
<th>Model</th>
<th>Power (W)</th>
<th>Speed (mm/s)</th>
<th>Hatch (mm)</th>
<th>Layer Thickness (micron)</th>
<th>Rotation Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSFC</td>
<td>CL</td>
<td>M1</td>
<td>180</td>
<td>600</td>
<td>.105</td>
<td>30</td>
<td>90</td>
</tr>
<tr>
<td>LAB A</td>
<td>EOS</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>LAB B</td>
<td>EOS</td>
<td>M270</td>
<td>195</td>
<td>-</td>
<td>-</td>
<td>40</td>
<td>67</td>
</tr>
<tr>
<td>LAB C</td>
<td>EOS</td>
<td>M280</td>
<td>305</td>
<td>1010</td>
<td>.110</td>
<td>40</td>
<td>67</td>
</tr>
<tr>
<td>Lab D</td>
<td>EOS</td>
<td>M280</td>
<td>285</td>
<td>960</td>
<td>N/A</td>
<td>40</td>
<td>67</td>
</tr>
</tbody>
</table>
Round Robin: **Microstructure**

- As-built microstructures are dominated by the characteristics of the melt pool, which vary based on build parameters.
- Following heat treatment, the microstructure recrystallizes and resembles the wrought microstructure, with some expected grain size variation. IN718 derives strength properties from precipitates in the nickel matrix, which are produced during the solution and aging heat treatments.
Round Robin: Low Cycle Fatigue

- Low-Cycle Fatigue Life was found to be reduced by the presence of Lack of Fusion (LOF) defects
- High-Cycle Fatigue life at a particular stress trended along with ultimate tensile strength, as expected.
Round Robin: Tensile Properties

- At room temperature, most builds exhibited tightly grouped results, with the exception of Lab D, which has considerable variability in ductility (fracture elongation).
- From past experience, lower elongation is an indication that defects were present in the material.
• MSFC-STD-3716 identifies AM as a unique material product form and requires the metallurgical process to be qualified (QMP) on *every* individual AM machine

• Developed from internal process specifications with likely incorporation of forthcoming industry standards.
Qualified Metallurgical Process

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 post-processing for controlled microstructural evolution
- Mechanical behavior reference data
  - Strength, ductility, fatigue
Qualified Metallurgical Process (QMP)

- As-built densification, microstructure, and defect state
- Thermal process for controlled microstructural evolution

As Built  Stress Relieved  HIP & Final
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
• 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
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 Manufacturing 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 Qualification Challenges

- 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
parts shall receive comprehensive NDE for volumetric and surface defects within the limitations of technique and part geometry. 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.

S defects shall be detected at the accepted probability of detection (POD), e.g., 90/95, for fracture critical applications. Demonstration parts with simulated CIFS defects are used to demonstrate NDE detection capability.

Demonstration of adequate part life starting from NASA-STD-599 flaw sizes is generally inappropriate for fracture critical, damage tolerant AM parts.

Class A parts, NDE indications of cracks, crack-like defects, or other findings of undetermined source should be elevated to senior review and disposition per applicable fracture control policy.
• 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 regions 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 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 standard defect classes for welds and castings welding or casting defect quality standards will generally not be applicable.**
• Standards with NDE acceptance criteria for welding or casting quality are not considered applicable to L-PBF hardware.
• 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.**
Upcoming Meetings
COLLABORATION ON QUALITY IN THE SPACE AND DEFENSE INDUSTRIES

March 12 – 13, 2018 | Cape Canaveral, FL

SUSTAINING A QUALITY FOUNDATION IN CHALLENGING TIMES

https://asq.org/conferences/quality-space-defense
TO: Members of ASTM Committees E08, F04 and F42

CALL FOR PAPERS

Fourth Symposium on Fatigue and Fracture of Metallic Medical Materials and Devices
May 22-23, 2018
San Diego, CA

The deadline to submit an abstract is October 13, 2017.

ABOUT THE EVENT
Papers are invited for the Fourth Symposium on Fatigue and Fracture of Metallic Medical Materials and Devices to be held May 22-23, 2018. Sponsored by ASTM Committees E08 on Fatigue and Fracture and F04 on Medical and Surgical Materials and Devices, the symposium will be held at the Sheraton San Diego Hotel & Marina in San Diego, CA, in conjunction with the May standards development meetings of both committees.

OBJECTIVES
The intent of this symposium is to provide an updated set of unique presentations on fatigue and fracture mechanics principles as applied to the fatigue, fracture, durability and life predictive methodologies involved in metallic medical materials and devices. Such materials include Nitinol, 304, 316L, other stainless steels, MP35N, Ti-6-4, Ti-15Mo, and Co-Cr. Any metallic medical devices with fatigue and fracture issues are of interest, such as pacemaker/defibrillator leads, stents, endovascular grafts, heart valve frames, occlusion devices, prosthetics, and circulatory assist devices. We intend to have several Invited Presentations from experts in this area of mechanics who will begin key sessions for this symposium.

The symposium will illustrate, with up-to-date presentations focused on medical device materials and devices:
• proven and new fatigue and fracture mechanic techniques that are being applied successfully;
• the design and durability assessment where crack propagation is of major consideration;
• the utility of existing fatigue and fracture mechanics standards in analyzing medical devices;
• fatigue initiation and propagation based methods for interpreting cyclic stress and strain tensor data from computational analysis for fatigue life predictions and analysis;
• patients medical device boundary conditions and duty cycles;
• metallic advanced manufacturing processes and devices;
• additional topics as appropriate

http://www.astm.org/E08F04Symp2018
Any Questions?

THIS IS ONLY THE BEGINNING

Point of contact:
Dr. Jess M. Waller
NASA White Sands Test Facility
 Telephone: (575) 524-5249
jess.m.waller@nasa.gov

Or a great place to get involved even if you’ve been doing this for a while
Back-ups
Qualified Metallurgical Process

Types of AM build witness specimens

- Metallurgical
- Tensile (strength 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 indirect indicator of AM part quality through inference.
Qualified Metallurgical Process

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 $\geq 0$

- $\mu_{\text{witness}}$

- $\sigma_{\text{witness}}$

DVS

- DVS 99/95 (design)

- $\mu$, $1\sigma$
Certification/Witness for Statistical Process Control

Example of AM build witness specimen evaluations

Nominal process is blue, off nominal in red

Two (2) witness tests per build

Six (6) witness tests per build

Random draw from nominal process 10 times

Random draw from off-nominal process, 10 times

Process shift hard to discern

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
Qualification & Certification/Witness for Statistical Process Control

- QMP
- AM Design Value Suite
- Characterization builds
  - PCWS consistent with PCR D
  - Test Specimens
- Part builds
  - PCWS
  - First Article/WS

Registration

Design and Analysis
• 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