NASA OSMA NDE Program
Additive Manufacturing Foundational Effort

Jess Waller (NASA WSTF), James Walker (NASA MSFC), Eric Burke, (NASA LaRC), Douglas Wells (NASA MSFC)

9th ESA-JAXA-NASA S&MA Trilateral Meeting, ISAS, Sagamihara, Japan
Wednesday 14 September 2016 – F2F Meeting, Day 2
Qualification of products fabricated via additive manufacturing
9:40 to 10:20 am JST
Background

- NASA is providing key leadership in an international effort linking NASA and non-NASA resources to speed adoption of additive manufacturing (AM) to meet NASA’s mission goals. Participants include industry, NASA’s space partners, other government agencies, standards organizations and academia:

- Nondestructive Evaluation (NDE) is identified as a universal need for all aspects of additive manufacturing.
Background

Contacts: Jess Waller (WSTF); James Walker (MSFC); Eric Burke (LaRC)

- NASA Agency additive manufacturing efforts were catalogued
- Industry, government and academia were asked to share their NDE experience in additive manufacturing
- NIST and USAF additive manufacturing roadmap were surveyed and a technology gap analysis performed
- NDE state-of-the-discipline was documented
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

EBF³ wire-fed system during parabolic flight testing

28-element Inconel 625 fuel injector

Prototype titanium to niobium gradient rocket nozzle

Made in Space AMF on ISS

Dynetics/Aerojet Rocketdyne F-1B gas generator injector

SpaceX SuperDraco combustion chamber for Dragon V2

ISRU regolith structures

Aerojet Rocketdyne RL-10 engine thrust chamber assembly and injector
NDE of AM Technology Gaps

- 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)
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NDE-based AM Part Qualification & Certification

Concept

Design for Powder Bed Fusion
- Build box limitations
- Self-supporting design
- Powder and Support removal
- Finishing allowances
- Surface texture requirements

Structural Assessment
- Material Properties

Part Classification
- Consequence of failure
- Build complexity
- Structural margins

Model Processing
- File formats
- Support integration
- Platform layout
- Part build orientation
- Lot acceptance

Build Vendor
- Quality system
- Qualification

Blend Lot
- Chemistry
- Mixing
- Distribution

Virgin Powder
- Qual control spec
- Certification/analysis

Feedstock
- Sieving
- Environment control
- Re-use limitations

Recycled Powder
- Solution treat or anneal
- Precipitation age

Thermal Processing
- Machining
- Peel/strip/blasting
- Peening
- Honing/polishing
- Etching
- Cleaning

Finishing Operations
- Part and lot acceptance
- Stress relief
- HIP
- Solution treat or anneal
- Precipitation age

Final Inspection/Acceptance
- Dimensional
- Surface finish
- Final part PT, ET, UT, CT
- Lot acceptance test/result
- Process certification records

Part

Component Development Plan
- Planning for all operations from Concept to Part
- Written prior to handoff from design to build

Model Quality
- Integrity of solid
- Model checking
- Version control

Hand-off From Design to Build

Build Lot Execution
- Platform selection
- Coater selection
- Powder selection
- Build parameters
- Build data collection
- Chamber environment
- Restart policies
- Post-build
- Powder removal
- Platform removal
- Repair policies

Raw Part Inspection
- Visual
- Radiography or CT
- Metallurgical
- Dimensional

in-process NDE

post-process NDE

post-process NDT
ASTM WK47031, NDE of metal parts used in aerospace applications (NASA leadership)

- First defect catalogues to show defect ↔ NDE linkage
- Process method determines defects
- Defect type & part complexity determine NDE selection
Background

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

<table>
<thead>
<tr>
<th>Flaw type</th>
<th>Non-NDT</th>
<th>Common in DED &amp; PBF</th>
<th>Unique to AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor surface finish</td>
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<tr>
<td>Porosity</td>
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<tr>
<td>Incomplete fusion</td>
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<td>Lack of geometrical accuracy/steps in part</td>
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<tr>
<td>Undercuts</td>
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<tr>
<td>Non-uniform weld bead and fusion characteristic</td>
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<tr>
<td>Hole or void</td>
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<td></td>
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<tr>
<td>Non-metallic inclusions</td>
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<tr>
<td>Cracking</td>
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</table>

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<th>Non-NDT</th>
<th>Common in DED &amp; PBF</th>
<th>Unique to AM</th>
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</thead>
<tbody>
<tr>
<td>Unconsolidated powder</td>
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<tr>
<td>Lack of geometrical accuracy/steps in part</td>
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<tr>
<td>Reduced mechanical properties</td>
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<tr>
<td>Inclusions</td>
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<tr>
<td>Void</td>
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<td></td>
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<tr>
<td>Layer</td>
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<td></td>
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<tr>
<td>Cross layer</td>
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<td></td>
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<tr>
<td>Porosity</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Poor surface finish</td>
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<tr>
<td>Trapped powder</td>
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Note: DED = Directed Energy Deposition., PBF = Powder Bed Fusion

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### 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>EBF&lt;sup&gt;3&lt;/sup&gt;</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.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>features interrogated</strong></td>
<td>complex geometries; large/thick/dense and very thin cross sections; (universal NDE standard, slabs, rods, gage blocks)</td>
<td>rectangular prisms, rows of cylinders, cylinders, flat-bottom holes, cone</td>
<td>steps, flat bottom holes</td>
<td>bead arrays, steps, holes</td>
<td>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 EBF&lt;sup&gt;3&lt;/sup&gt; 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 IQ! 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>
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Determine effect-of-defect on sacrificial specimens with seeded flaws

Airbus Laser Powder Bed Fusion (PBF) samples

Advratech Laser PBF samples (in progress§)

Investigate effect post-processing on microstructure and surface finish on fatigue properties

AISi10Mg ASTM E8 compliant dogbones
13mmØ, 85mm long (6mmØ, 30mm Gauge Length)

§ FY17 STTR T12.04-9979 Real-Time Geometric Analysis of Additive Manufacturing status (NASA MSFC) Develops a novel process control and part documentation solution for selective laser melting (SLM) additive manufacturing.

Ti-6Al-4V ASTM E8 compliant dogbones for in situ OM/IR and post-process profilometry, CT and PCRT
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Background

Contact: Doug Wells (MSFC)

- Comprehensive draft technical standard is in review
- All Class A and B parts are expected to receive comprehensive NDE for surface and volumetric defects within the limitations of technique and part geometry
- Not clear that defect sizes from NASA-STD-5009§ are applicable to AM hardware
- NDE procedural details are still emerging

§ NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components
Background

Comprehensive NDE required for surface and volumetric defects

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§ NASA classifications should not to be confused with those used in the ASTM International standards for AM parts, such as F3055 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion. The ASTM classes are used to represent part processing only and are unrelated.
FY16 Continuing Projects

- An Assessment of NDE Capability and Materials Characterization for Complex Additive Manufacturing Aerospace Components (Walker, Martin)
- Foundational Methodology for Additive Manufacturing Investigation of NDE Flaw Detectability in AM Parts (Koshti, Stanley, Taminger, Hafley, Brice, Burke)
- X-ray Computed Tomography Image Quality Indicator Development (Jones, Fischetti, Kent)
- KSC Foundational Methodol. for Additive Manuf. – Electron Beam Melting NDE (Skow)
- Evaluation of Additively Manufactured Metals for use in Oxygen Systems (Tylka)
- NDE of Aerospace Parts (including Additive Manufactured) Voluntary Censensus Organization Standards and Related Round-Robin Tests (Waller, Nichols)
FY17 New Starts

- A Quantitative Assessment of NDE Capability on Additive Manufactured (Selective Laser Melting) Inconel 718 (Walker, Martin)

Additive Manufacturing Structural Integrity Initiative (AMSII)

- Involves the characterization of defect structures of selective laser melting (SLM) Inconel® 718 material within the nominal process window and its limits, build test articles for NDE studies and correlation with destructive test results.
- Relevance to parts made for Commercial Crew Program (CCP), Space Launch System (SLS) and Multipurpose Crew Vehicle (MPCV).
Questions?

THIS IS ONLY THE BEGINNING

[Diagram showing logos of various organizations including NASA, ESA, America Makes, Airbus, SpaceX, Boeing, and others.]