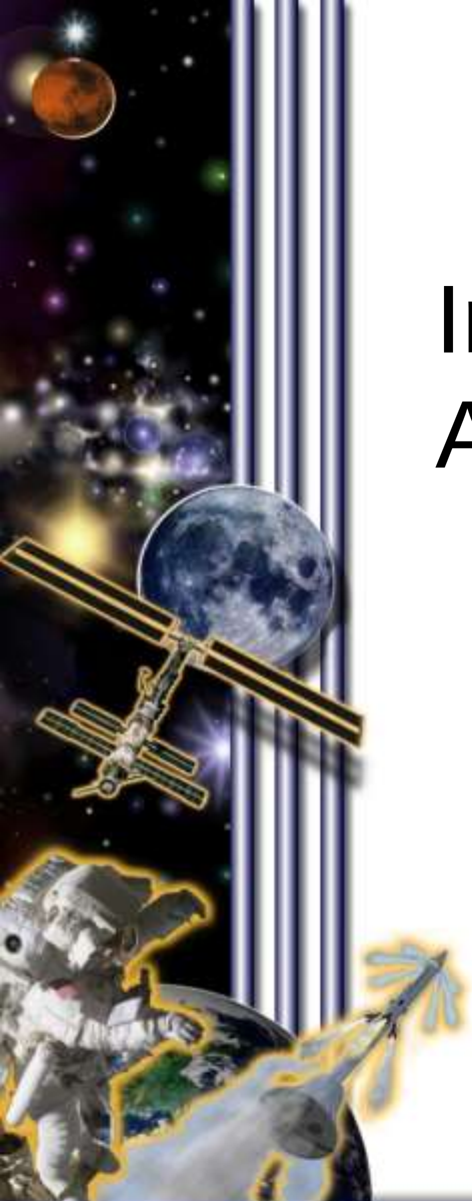


Initiatives to Improve Quality of Additively Manufactured Parts

Jess Waller ♦ NASA WSTF

Charles Nichols ♦ NASA WSTF

Additive Manufacturing Product Qualification Initiatives

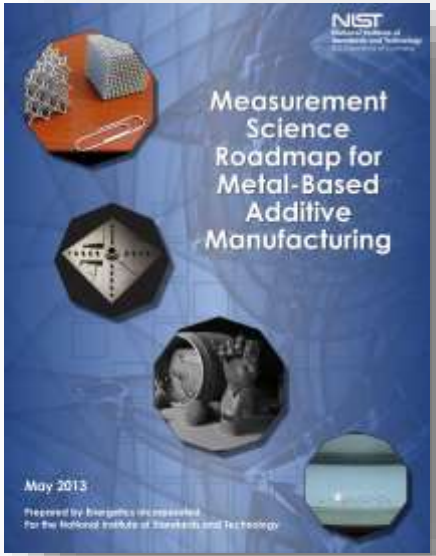
Webinar

ASTM E07.10 Taskgroup on NDT of Aerospace Materials
Monday, June 12, 2017

Background

- NASA is providing leadership in an international effort linking government and industry resources to speed adoption of additive manufactured (AM) parts
- Participants include government agencies (NASA, USAF, NIST, FAA), industry (commercial aerospace, NDE manufacturers, AM equipment manufacturers), standards organizations and academia
- NASA is also partnering with its international space exploration organizations such as ESA and JAXA
- NDT is identified as a universal need for all aspects of additive manufacturing

Key Documents to Improve Safety and Reliability of AM Parts using NDE


NIST

Measurement Science Roadmap for Metal-Based Additive Manufacturing

May 2013


NASA/TM—2014-218560

Nondestructive Evaluation of Additive Manufacturing

State-of-the-Discipline Report

November 2014

NASA
Additive Manufacturing
Roadmap and NDE-related
Technology Gaps


AFRL-RX-WP-TR-2014-0162

AMERICA MAKES: NATIONAL ADDITIVE MANUFACTURING INNOVATION INSTITUTE (NAMII)
Project 1: Nondestructive Evaluation (NDE) of Complex Metallic Additive Manufactured (AM) Structures

EWI

JUNE 2014
Interim Report

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

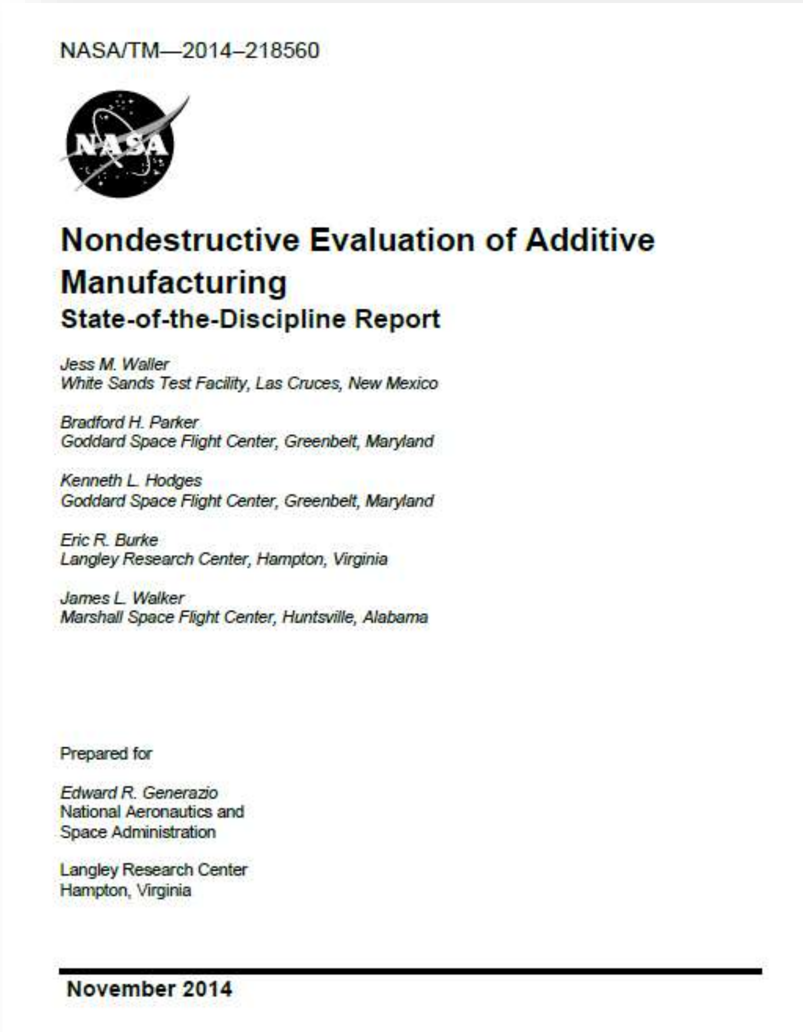

EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

Background


NASA/TM—2014–218560

Nondestructive Evaluation of Additive Manufacturing
State-of-the-Discipline Report

Jess M. Waller
White Sands Test Facility, Las Cruces, New Mexico

Bradford H. Parker
Goddard Space Flight Center, Greenbelt, Maryland

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Goddard Space Flight Center, Greenbelt, Maryland

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James L. Walker
Marshall Space Flight Center, Huntsville, Alabama

Prepared for

Edward R. Generazio
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia

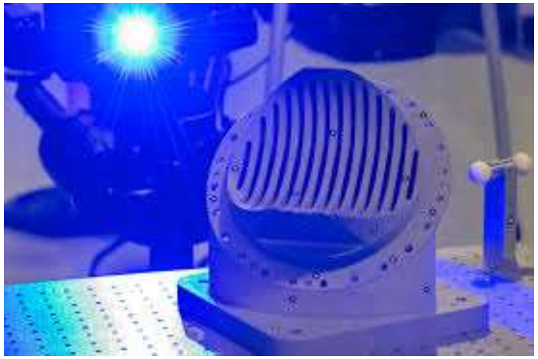
November 2014

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

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

Representative NASA Efforts in Additive Manufacturing

NASA Agency & Prime Contractor Activity, ca. 2014



MSFC Inconel Pogo-Z baffle for RS-25 engine for SLS

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

LaRC EBF^3 wire-fed system during parabolic fight testing

MSFC 28-element Inconel 625 fuel injector

JPL Prototype titanium to niobium gradient rocket nozzle

MSFS-AMES 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

Commercial Crew Program SpaceX SuperDraco combustion chamber for Dragon V2

NASA Agency & Prime Contractor Activity, Recent

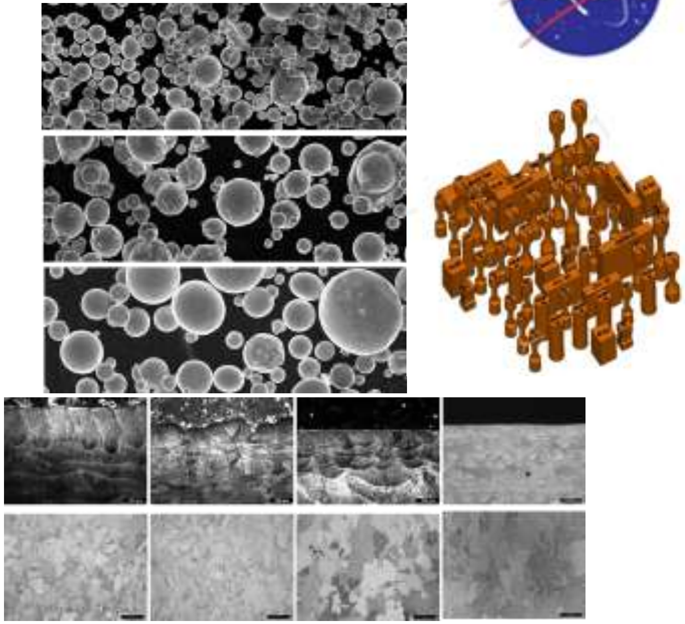
JPL Mars Science Laboratory Cold Encoder Shaft fabricated by gradient additive processes

MSFC copper combustion chamber liner for extreme temperature and pressure applications

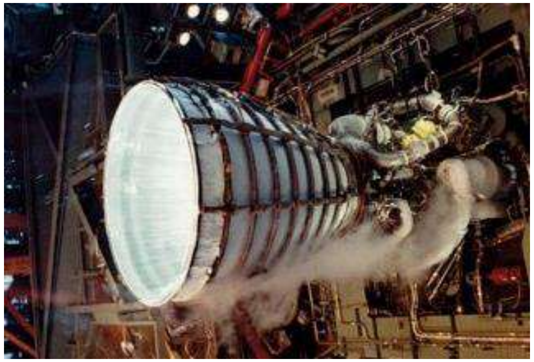
NASA-sponsored 3-D Printed Habitat Challenge Design Competition

MSFC rocket engine fuel turbopump

NASA Space Technology Mission Directorate-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



MSFC Space Launch System NASA's RS-25 core stage engine certification testing

Additive Manufacturing Technology Gap Analysis

NDE of AM Technology Gaps

- Develop in-situ monitoring to improve feedback control, maximize part quality and consistency, and obtain ready-for-use certified parts
- Develop and refine NDE of as-built and post-processed AM parts
- Develop voluntary consensus standards for NDE of AM parts
- Develop better physics-based process models using and corroborated by NDE
- Use NDE to understand scatter in design allowables database generation activities (process-structure-property correlation)
- Fabricate AM physical reference samples to demonstrate NDE capability for specific defect types
- Apply NDE to understand effect-of-defect, and establish acceptance limits for specific defect types and defect sizes
- Develop NDE-based qualification and certification protocols for flight hardware (screen out critical defects)

NDE of AM Technology Gaps

- Develop a defects catalogue for AM parts — NEW gap identified
- 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
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Identify Relevant AM Defects

Identify Relevant AM Defects

➡ Why do we care about defects?

Defects – Process route effects

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.

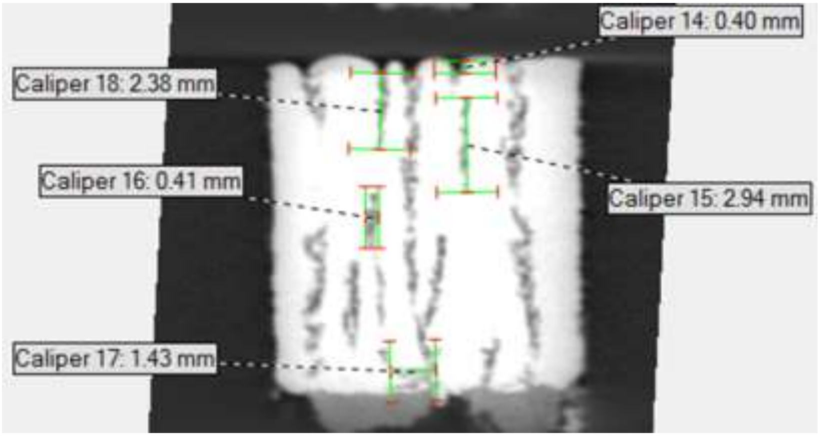
	Flaw type	Non- NDT	Common in DED & PBF	Covered by current standards	Unique to AM
DED	Poor surface finish	■	■		
	Porosity		■	■	
	Incomplete fusion			■	
	Lack of geometrical accuracy/steps in part	■	■		
	Undercuts			■	
	Non-uniform weld bead and fusion characteristic			■	
	Hole or void		■	■	
	Non-metallic inclusions		■	■	
	Cracking		■	■	
PBF	**Unconsolidated powder**				■
	Lack of geometrical accuracy/steps in part	■	■		
	Reduced mechanical properties	■			
	Inclusions		■	■	
	Void		■	■	
	Layer				■
	Cross layer				■
	Porosity		■	■	
	Poor surface finish	■	■		
	Trapped powder				■

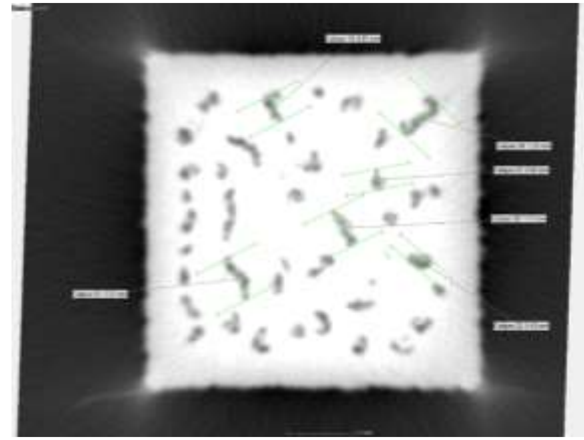
Develop new NDE methods

§ ISO TC 261 JG59, Additive manufacturing – General principles – Nondestructive evaluation of additive manufactured products, under development.

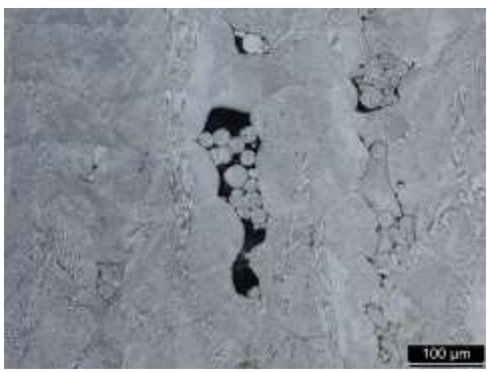
Note: DED = Directed Energy Deposition., PBF = Powder Bed Fusion

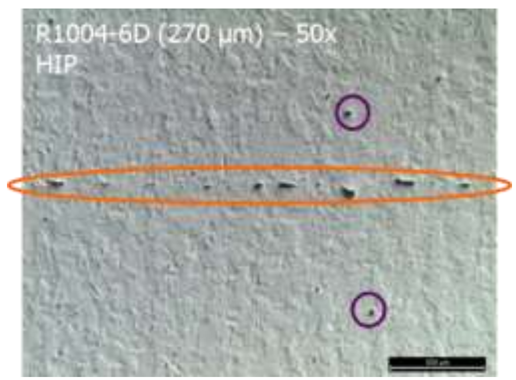
Typical PBF Defects of Interest

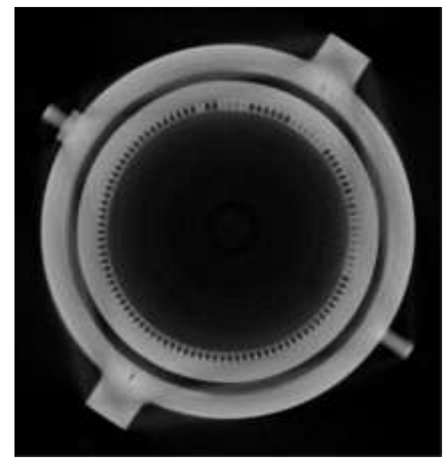




Cross layer







Lack of Fusion (LOF)

Layer

Trapped Powder

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

Use of Nondestructive Evaluation to Detect Defects of Interest

Designation: X XXXX-XX

Work Item Number: 47031

Date: May 3, 2017

TABLE 4.3 Application of NDT to Detect Additive Manufacturing Defect Classes[A]

	Covered in this Guide						Not covered in this Guide					
Defect Class	**CT/RT/ CR/DR**	**MET[B]**	**PCRT**	**PT**	**TT**	**UT**	**AE**	**ECT**	**LT**	**ND**	**MT**	**VT**
Surface	...	X	...	X[C]	...	...	...	...	...	...	...	X
Porosity	X	...	X	X[C]	...	X	...	X[C]	...	...	...	X[D]
Cracking	X	...	X	X[C]	X	X	X	X[C]	X[E]	...	X	X
Lack of Fusion	X	...	X	X[C]	X	X	X	X[C]	...	...	X	...
Part Dimensions	X	X	...	...	...	...	...	...	...	...	...	...
Density[F]	X[G]	...	...	...	...	...	...	...	...	...	...	...
Inclusions	X[H]	...	...	...	X	X	...	...	...	...	...	...
Discoloration	...	...	...	...	...	...	...	...	...	...	...	X
Residual Stress	...	...	...	...	...	...	...	...	...	X	...	...
Hermetic Sealing	...	...	...	...	...	...	...	...	X	...	...	...

[A] Abbreviations used: ··· = not applicable, Acoustic Emission, CR = Computed Radiology, CT, = Computed Tomography, Dr = Digital Radiology, ECT = Eddy Current Testing, Leak Testing = LT, MET = Metrology, MT = Magnetic Particle Testing, ND = Neutron Diffraction, PCRT = Process Compensated Resonance Testing, PT = Penetrant Testing, RT = Radiographic Testing, TT = Thermographic Testing, UT = Ultrasonic Testing, VT = Visual Testing.

[B] Includes Digital Imaging.

[C] Applicable if on surface.

[D] Macroscopic cracks only.

[E] If large enough to cause a leak or pressure drop across the part.

[F] Pycnometry (Archimedes principle).

[G] Density variations will only show up imaged regions having equivalent thickness.

[H] If inclusions are large enough and sufficient scattering contrast exists.

- **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 and Capture Best NDE Practice

Develop and Capture Best NDE Practice

- 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
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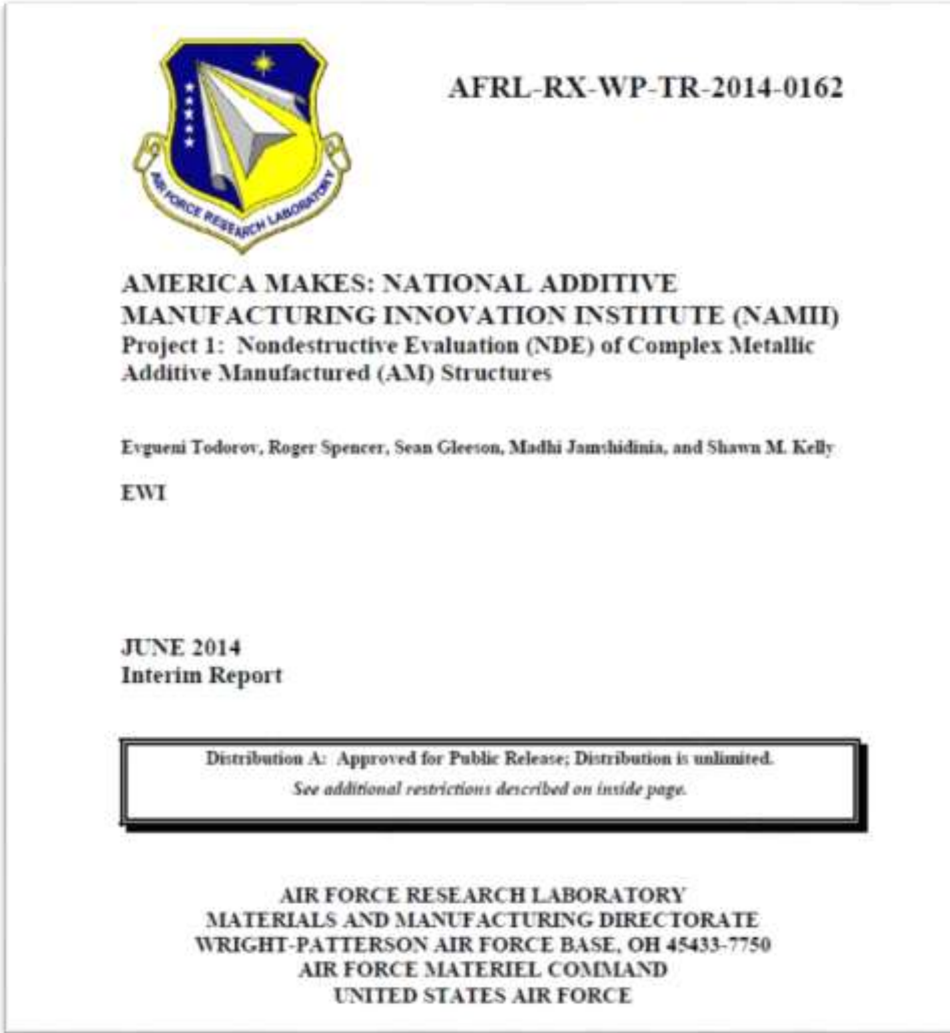
Effect of Design Complexity on NDE/USAF Findings



AFRL-RX-WP-TR-2014-0162

AMERICA MAKES: NATIONAL ADDITIVE MANUFACTURING INNOVATION INSTITUTE (NAMII)
Project 1: Nondestructive Evaluation (NDE) of Complex Metallic Additive Manufactured (AM) Structures

Evgueni Todorov, Roger Spencer, Sean Gleeson, Madhi Jamshidinia, and Shawn M. Kelly

EWI

JUNE 2014
Interim Report

Distribution A: Approved for Public Release; Distribution is unlimited.
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MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

Contact: *Evgueni Todorov (EWI)*

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

Effect of Design Complexity on NDE/USAF Findings

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):

1

2

3

4

5

§ Kerbrat, O., Mognol, P., Hascoet, J. Y., *Manufacturing Complexity Evaluation for Additive and Subtractive Processes: Application to Hybrid Modular Tooling*, IRCCyN, Nantes, France, pp. 519-530, September 10, 2008.

Effect of Design Complexity on NDE/USAF Findings


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NDE Technique	Geometry Complexity Group					Comments
	1	2	3	4	5	
VT	Y	Y	P(c)	NA	NA	
LT	NA	NA	Y	Y	NA	Screening
PT	Y	Y	P(a)	NA	NA	
PCRT	Y	Y	Y	Y	Y	Screening; size restrictions (e.g., compressor blades)
EIT	Y	Y	NA	NA	NA	Screening; size restrictions
ACPD	Y	Y	P(c)	NA	NA	Isolated microstructure and/or stresses
ET	Y	Y	P(c)	NA	NA	
AEC	Y	Y	P(c)	NA	NA	
PAUT	Y	Y	P(b)	NA	NA	
UT	Y	Y	P(b)	NA	NA	
RT	Y	Y	P(d)	NA	NA	
X-Ray CT	Y	Y	Y	Y	NA	
X-ray Micro CT	Y	Y	Y	Y	Y	

Key:

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

Notes:

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

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

Demonstrate NDE Capability through Round Robin Testing

ASTM E07.10 WK47031 Round Robin Testing Participants

CT/MET, MSFC/James Walker
*metal SLM parts, MSFC/Kristin Morgan
*ABS plastic parts, MSFC/Niki Werkheiser, Tracie Prater
CT, GSFC/Justin Jones
*EBF3 metal parts, LaRC/Karen Taminger

→ NASA

POD/fracture critical AM parts, ESA/Gerben Sinnema

→ ESA

AE, MRI/Ed Ginzel
CT/acoustic microscopy, Honeywell/Surendra Singh
UT/PT, Aerospace Rocketdyne/Steve James
CT/RT, USAF/John Brausch, Ken LaCivita
CT, Fraunhofer/Christian Kretzer
CT, GE Sensing GmbH/Thomas Mayer
CT, JAXA/Tabuchi Teruhiko, Kazuhiro Nakamura
PCRT, Vibrant Corporation/Eric Biedermann
PT, Met-L-Check/Mike White

→ Commercial/Gov NDE

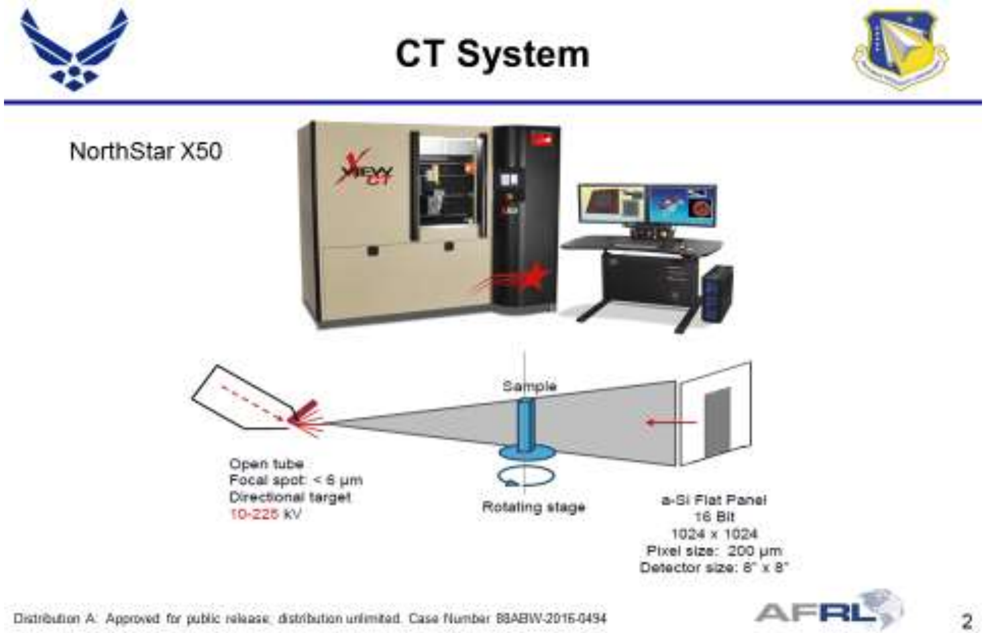
NRUS, LANL/Marcel Remillieux
*Concept Laser/Marie Ebert
*DRDC/Shannon Farrell
†*Airbus/Amy Glover
†*UTC/John Middendorf, Wright State University/Greg Loughnane
†*CalRAM/Shane Collins

→ Commercial/Gov AM Round Robin Sample Suppliers

* delivered or committed to deliver samples
† E8 compliant sacrificial dogbone samples

1. CT and micro-CT:

AFRL and Fraunhofer micro-CT Systems



CT systems

	225 kV µCT	600 kV MacroCT
Tube	FXE 225.99 microfocus	Comet MXR 601/HP11 Minifocus
Focal spot	Approx. 10 µm variable	0,5 mm fixed (ASTM)
Detector	PerkinElmer XRD 1620 AN	PerkinElmer XRD 1621 EN
Pixelpitch	200 µm	200 µm
Prefilter	2,5mm copper	6-7 mm copper
Type	Helical CT	Standard CT
Proj.	1200 Proj/rot.	1600 Proj.

Fraunhofer EZRT

- Also utilize NASA CT capability at GSFC, MSFC and GRC
- GE Aviation and JAXA CT capability leveraged

2. Process Compensated Resonance Testing (PCRT):

Vibrant

Process Compensated Resonance Testing (PCRT) for Additive Manufacturing

Vibrant Corporation
8330A Washington Pl NE
Albuquerque, NM 87113
USA
+1 (505) 314 1488
www.vibrantndt.com

Vibrant

Standards and Approvals for PCRT

ASTM E2001-13 Standard Guide for Resonant Ultrasound Spectroscopy - outlines capabilities and applications of several resonant inspection methods

ASTM Standard Practice E2534-10 – Describes auditable method for successful application PCRT specifically and in-depth.

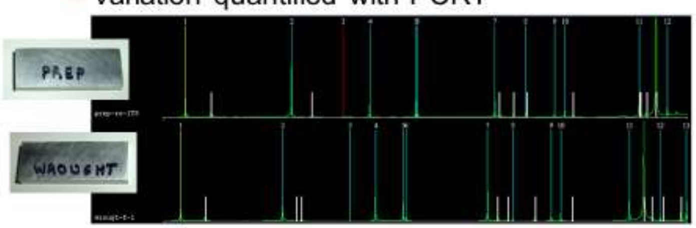
Federal Aviation Administration Approved – Since July of 2010 for the detection of micro-structural changes indicating over-temp of turbine blades (JT8D-219 HPT)

AS9100-C & ISO9001:2008 – Certificate #14-2057R issued by PRI Registrar

Vibrant

Titanium Samples

- Additive manufacturing vs. wrought
  - Same part, material variation between processes
  - Variation quantified with PCRT



12

Vibrant

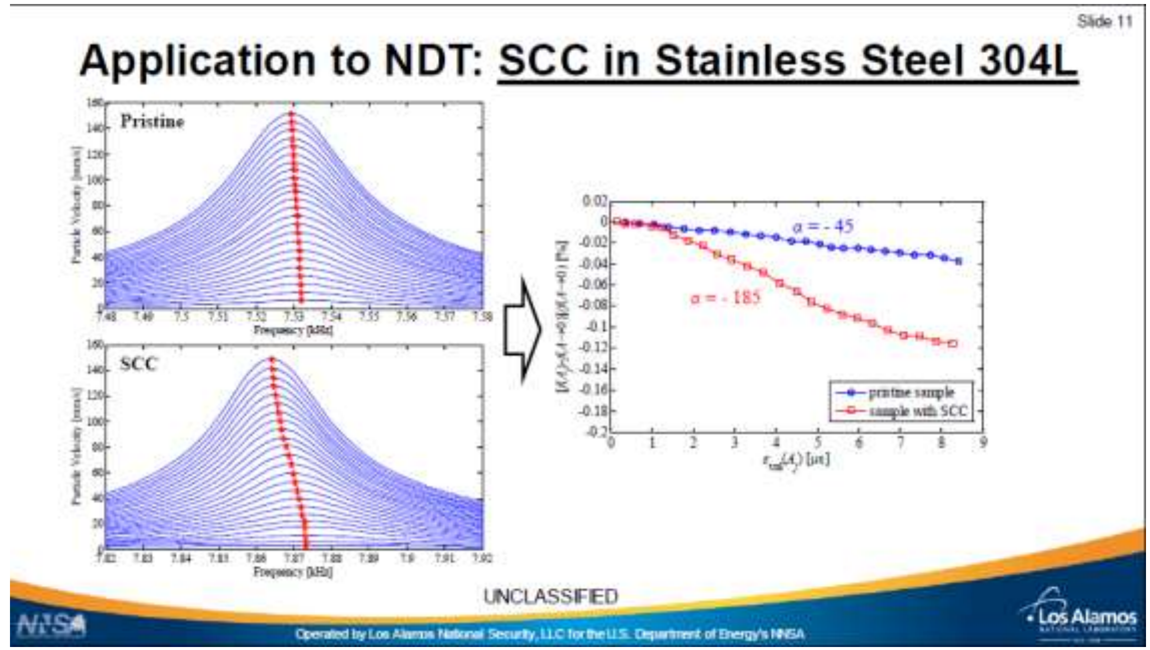
AM Process Variation

- Sensitivity to thermal process variation
  - FAA-approved JT8D overtemp at Delta
  - Works for additive manufacturing processes

11

PCRT also can distinguish processing effects, for example, SLM samples made with different laser scanning speeds (Ti6-4 Gong/Univ. of Louisville samples)

3. 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

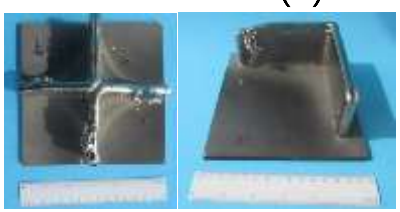
Coordinated by S. James (Aerojet Rocketdyne)

Electron Beam Freeform Fabrication (EBF^3)

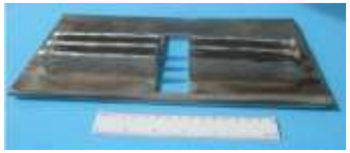
NASA LaRC

Inconel 625 on copper

Ti-6Al-4V (4)



SS 316



Al 2216

Laser-PBF (L-PBF)

Gong

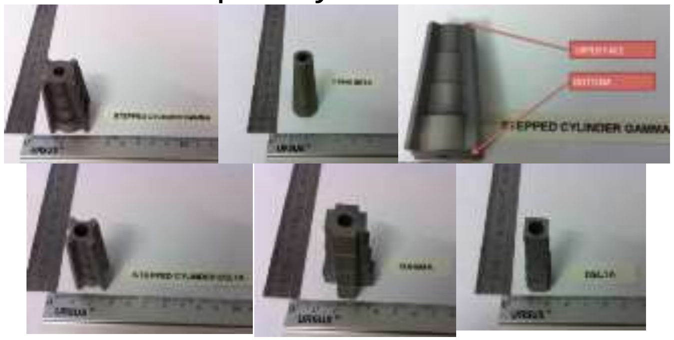
Ti-6Al-4V bars

Airbus

Al-Si-10Mg dog bones

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

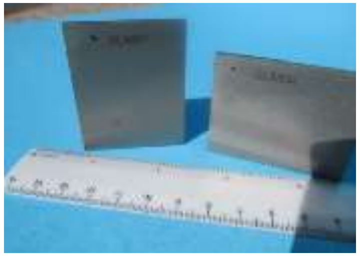
Concept Laser Inconel 718 prisms for CT capability demonstration



Electron Beam-PBF (E-PBF)

Met-L-Check

SS 316 PT/RT panels



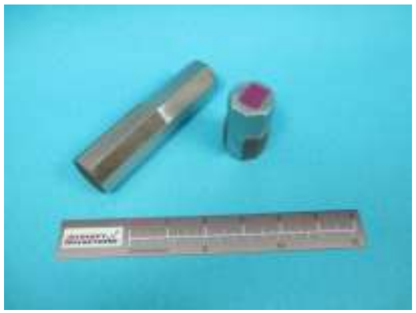
Characterized to date by various NDE techniques (CT, RT, PT, PCRT, UT)

ASTM WK47031 Round Robin Testing (Leveraged)

Coordinated by S. James (Aerojet Rocketdyne) and J. Waller (NASA WSTF)

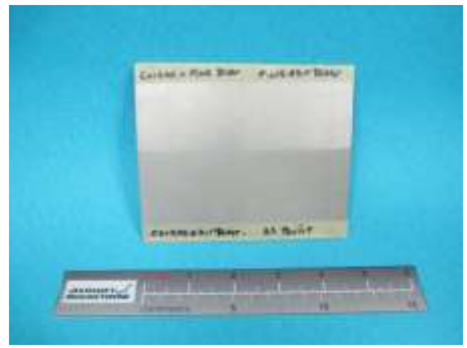
HEX Samples

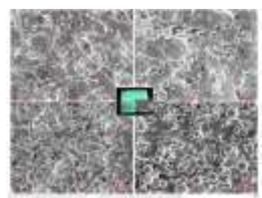
Inconel 718
in two different build orientations



SLM (L-PBF)

Inconel 625 PT sheets





Laser-PBF (L-PBF)

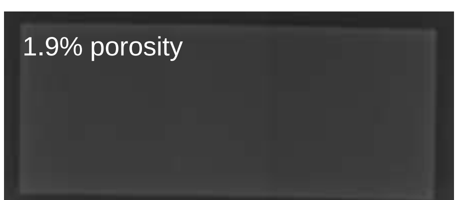
NASA MSFC nominal and off-nominal metal parts (K. Morgan)

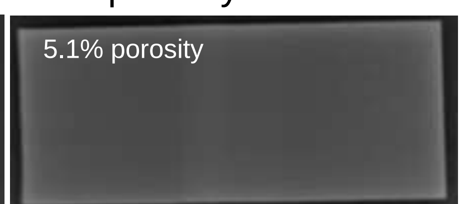
Directed Energy Deposition (DED)

NASA MSFC ABS plastic parts with and without defects (N. Werkheiser)

DRDC Porosity Standards

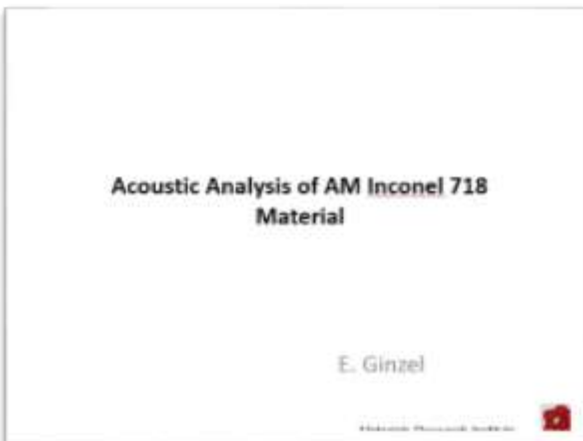
4140 steel. 0-10% porosity





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

Round Robin Sample Activity – illustrative presentations



Working drafts and minutes of webmeetings discussing the standard Guide for NDE of AM aerospace parts are posted on-line:

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

Voluntary Consensus Standards Gap Analysis

NDE of AM Technology Gaps

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

ANSI-America Makes National Collaborative Effort: Proposed New AM Standards

America Makes & ANSI AMSC Findings

- 181 members (June 2016)
- Walker, Wells, Luna and Waller among NASA-affiliated members on roster
- Standardization roadmap released in February 2017
- 89 standards gaps identified
  - 6 nondestructive evaluation gaps
  - 15 qualification and certification gaps
  - 6 precursor materials gaps
  - 17 process control gaps
  - 5 post-processing gaps
  - 5 finished materials gaps
  - 26 design gaps
  - 8 maintenance gaps
- Future meetings of Standards Development Organizations will discuss how the standards are divvied up

America Makes
National Additive Manufacturing Innovation Institute

ANSI
American National Standards Institute

- America Makes and ANSI Launch Additive Manufacturing Standardization Collaborative; Kick-off Meeting held March 31, 2016
- 5 Working Groups established to cover AM standards areas

<u>Non-Destructive Evaluation (NDE) WG</u>
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

<u>Qualification & Certification (Q&C) WG</u>
Meets: Every other Monday, 2:30 – 4 pm Eastern, beginning May 9, 2016
Co-chairs: Capt. Armen Kurdian, U.S. Navy, and Shawn Moylan, NIST

Ensure that all stages of a particular AM process have a set of commonly understood standards to enable Qualification (Qualification is defined as ensuring suitability to meet functional requirements in a repeatable manner)
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

ASME ISO ASTM INTERNATIONAL SAE AWS

America Makes & ANSI AMSC Roadmap

https://www.ansi.org/standards_activities/standards_boards_panels/amsc/amsc-roadmap:

America Makes
National Additive Manufacturing Innovation Institute

ANSI
American National Standards Institute

Standardization Roadmap for Additive Manufacturing

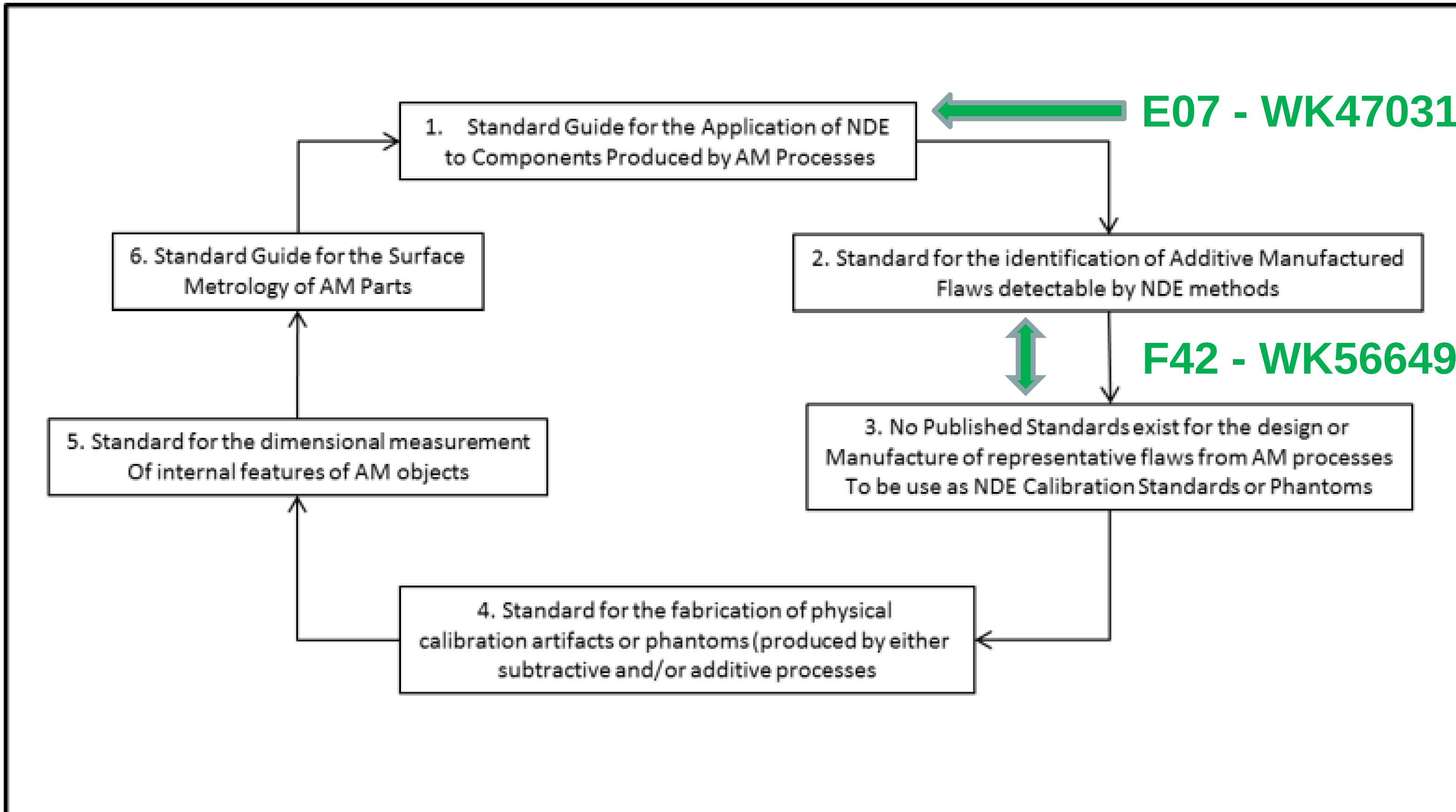
VERSION 1.0

PREPARED BY THE
America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)

FEBRUARY 2017

Gaps Identified by NDE Working Group

Standards in progress



Current and future NDE of AM standards under development (ASTM)

Draft: WK47031 POC: J. Waller

E07 Standard Guide for Nondestructive Testing of As-Built and Post-Processed Metal Additive Manufactured Parts Used in Aerospace Applications

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

Draft: WK56649 POC: S. James

F42 Standard Guide for Intentionally Seeding Flaws in Additively Manufactured Parts

Draft in Preparation

Draft: WKXXXX POC: S. Singh

E07 Standard Guide for In-situ Monitoring During the Build of Metal Additive Manufactured Parts Used in Aerospace Applications

Motion to register as a formal work item approved by E07.10 (IR, LUT, VIS)

Draft: WKXXXX POC: TBD

E07 Standard Practice for Dimensional Metrology of Surface and Internal Features in Additively Manufactured Parts

Future

Draft: WKXXXX POC: TBD

E07? Standard Practice for the Design and Manufacture of Artifacts or Phantoms Appropriate for Demonstrating NDE Capability in Additively Manufactured Parts

Future, phys ref stds to demonstrate NDE capability

High Priority Gaps Identified by Qualification and 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.

R&D Needed: No

Recommendation: Compare how the terms qualification, certification, verification and validation are used by industry sector. Update as needed existing quality management system standards and other terminology standards to harmonize definitions and encourage consistent use of terms across industry sectors with respect to AM.

Priority: High

Organization: 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 (2.3.2.2) and the NASA Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware (2.3.2.6). This is a gap for the aerospace and defense industries.

R&D Needed: No

Recommendation: A classification of parts should be defined as well as a minimum set of qualification requirements and related technology readiness level (TRL) and manufacturing readiness level (MRL) metrics for each part category that takes into consideration the intended part usage/environment. It is suggested that mission critical parts be looked at first.

Priority: High
Organization: NASA, SAE, ISO/ASTM

High Priority Gaps Identified by Qualification and Certification Working Group

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, the government will need to fully 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. Thus, not only must the government understand the differences, but how they should be assessed and tested, and what additional checks must be made on the end product before it can be qualified for use in a military platform. 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.

R&D Needed: Yes

Recommendation: Starting with the most mature technologies, such as laser powder bed, develop standards to assess required checks for levels of criticality and safety as part of the source approval process.

Priority: High

Organization: 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.

R&D Needed: No

Recommendation: 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.

Priority: High

Organization: SME, RSNA, ASTM

High Priority Gaps Identified by Qualification and Certification Working Group

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).

R&D Needed: Yes, in terms of tolerances

Recommendation: Develop standards for verification of the 3D model against the initial data. Ideally, they should identify efficient, automatable methods for identifying discrepancies.

Priority: High

Organization: ASTM, NEMA/MITA, AAMI, ASME, ISO

Understand Effect-of-Defect

NDE of AM Technology Gaps

- Develop/generate an AM defects catalogue (NEW)
- Develop in-process NDE to improve feedback control, maximize part quality and consistency, and obtain ready-for-use certified parts
- 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)
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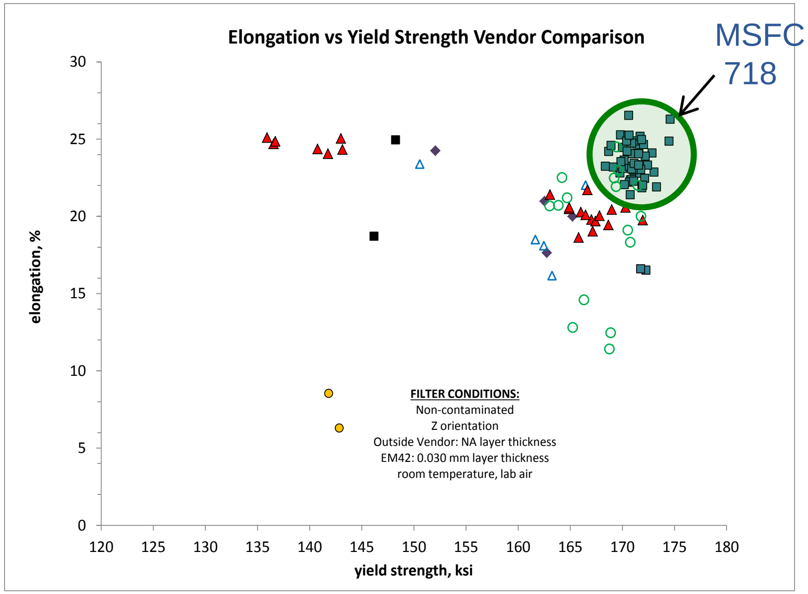
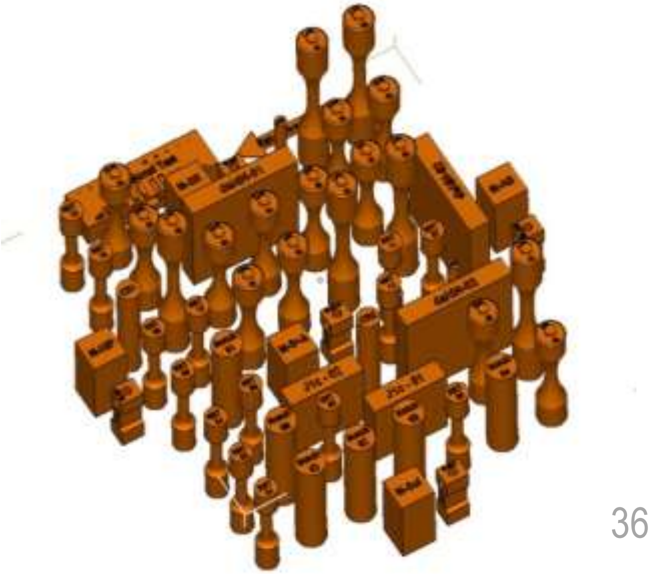
- Develop NDE-based qualification and certification protocols for flight hardware (screen out critical defects)

AM Inconel 718 Round Robin



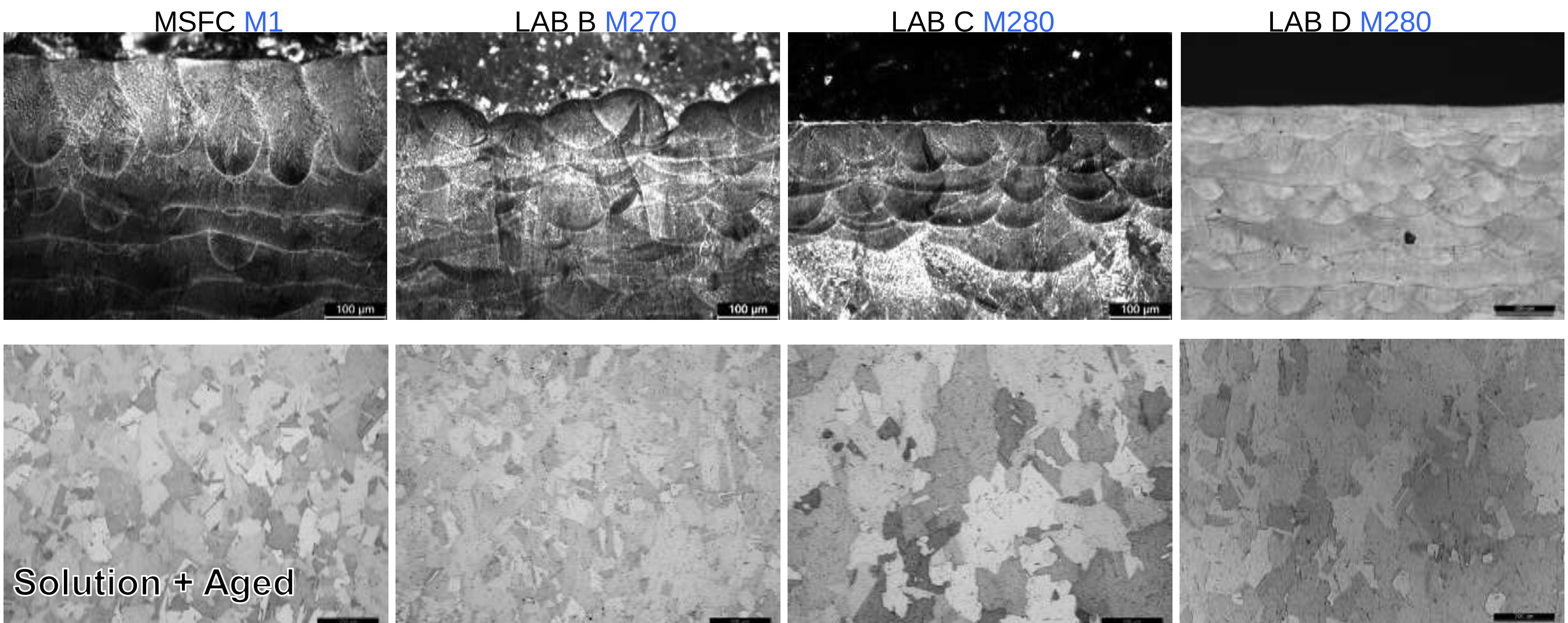
- Early comparisons of Inconel 718 produced by MSFC and by vendors indicated significant variations in mechanical and microstructural properties, which raised concerns about certification of parts produced via additive manufacturing.
- Participants used a variety of machine models, providing a diverse 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.

LAB	OEM	Model	Power (W)	Speed (mm/s)	Hatch (mm)	Layer Thickness (micron)	Rotation Angle
MSFC	CL	M1	180	600	.105	30	90
LAB A	EOS	-	-	-	-	40	-
LAB B	EOS	M270	195	-	-	40	67
LAB C	EOS	M280	305	1010	.110	40	67
Lab D	EOS	M280	285	960	N/A	40	67



Round Robin: Microstructure

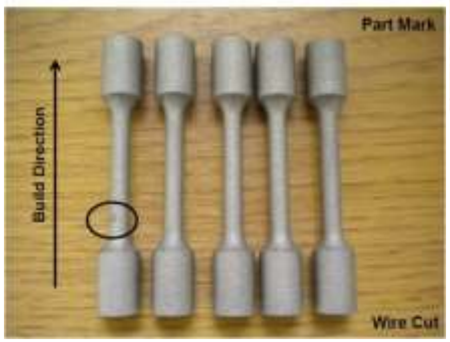
- As-built microstructures are dominated by the characteristics of the melt pool, which vary based on build parameters.
- Following heat treatment, the microstructure recrystallizes and resembles the wrought microstructure, with some expected grain size variation. IN718 derives strength properties from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



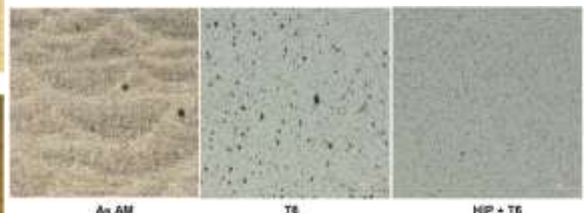
Approach

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

1. Airbus Laser PBF samples



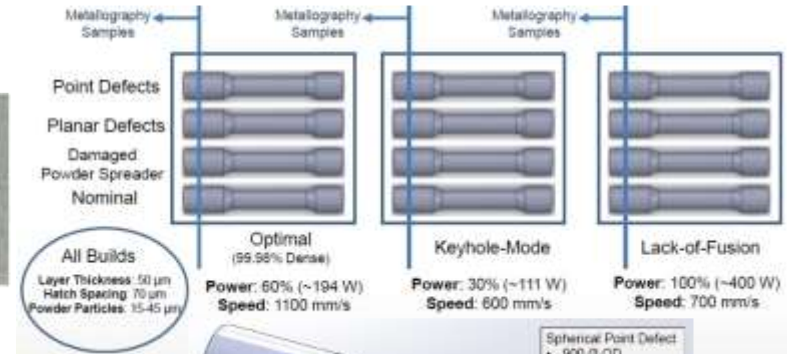
AlSi10Mg ASTM E8 compliant dogbones
13mmØ, 85mm long (6mmØ, 30mm Gauge Length)

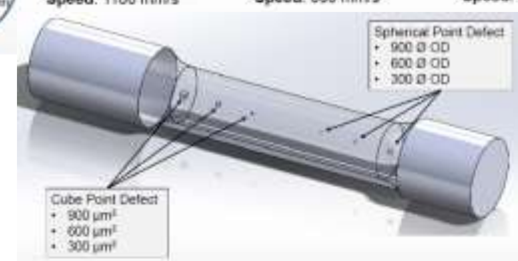


Investigate effect post-processing on microstructure and surface finish on fatigue properties

Airbus study on effect of process parameters on final properties

2. UTC Laser PBF samples





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

CT at GRC as of November

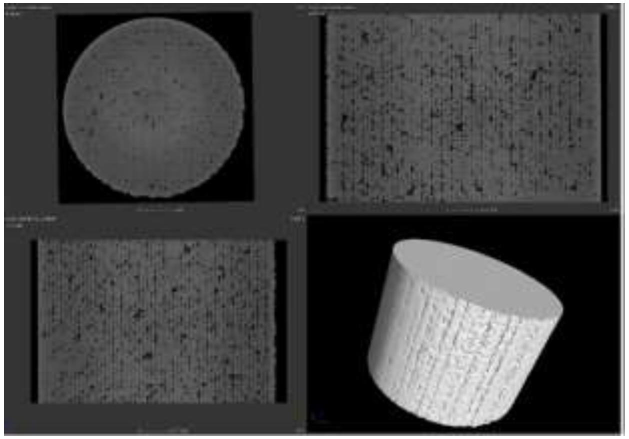
Other NDE planned in ASTM NDT Taskgroup

Parallel effort

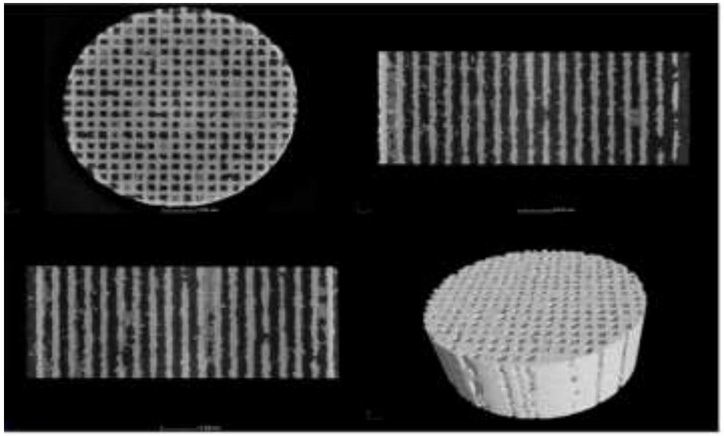
Determine effect-of-defect on sacrificial specimens w/ seeded flaws

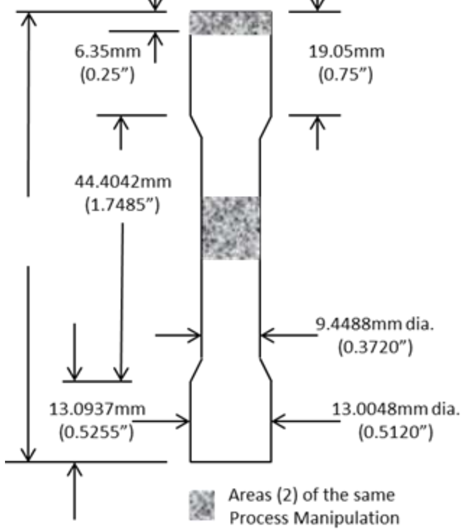
America Makes Ed Morris (VP) call to fabricate samples for NDE in support of ASTM WK47031 effort

Insert 1 "Lower Laser Power"



Insert 4 "Trace Width Bigger"





3. CalRAM Electron Beam PBF samples
4. Incodema Laser Beam PBF samples

Qualify & Certify Additively Manufactured Hardware

NDE of AM Technology Gaps

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


National Aeronautics and Space Administration

MSFC-STD-xxxx
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

This official draft has not been approved and is subject to modification.
DO NOT USE PRIOR TO APPROVAL

CHECK THE MASTER LIST—
VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED

Contact: *Doug Wells (MSFC)*

- All Class A and B parts must receive comprehensive NDT for surface and volumetric defects
- Not clear that defect sizes from NASA-STD-5009§ are applicable to AM hardware
- Has evolved into a Center-level standard and specification:
- MSFC-STD-3716: aids in the development of standard practices for Laser-Powder Bed Fusion processes
- MSFC-SPEC-3717: framework for the development, production, and evaluation of additively manufactured parts

NASA Engineering and Safety Center (NESC) publicity:

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 spaceflight (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)[1] to establish standard practices for the Laser Powder Bed Fusion (L-PBF) process. In its draft form, the MSFC standard has been used as a basis for L-PBF 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 content and scheduled release of these consensus standards do not support the near-term programmatic needs of NASA.

Aerojet Rocketdyne

RS-25 Engine

SpaceX

SuperDraco Engine

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 L-PBF processes. This standard and its companion specification[2], 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 L-PBF 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, assuring 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 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 promise 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
2. MSFC-SPEC-3717, "Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes," 2017

For information contact the NESC at www.nesc.nasa.gov

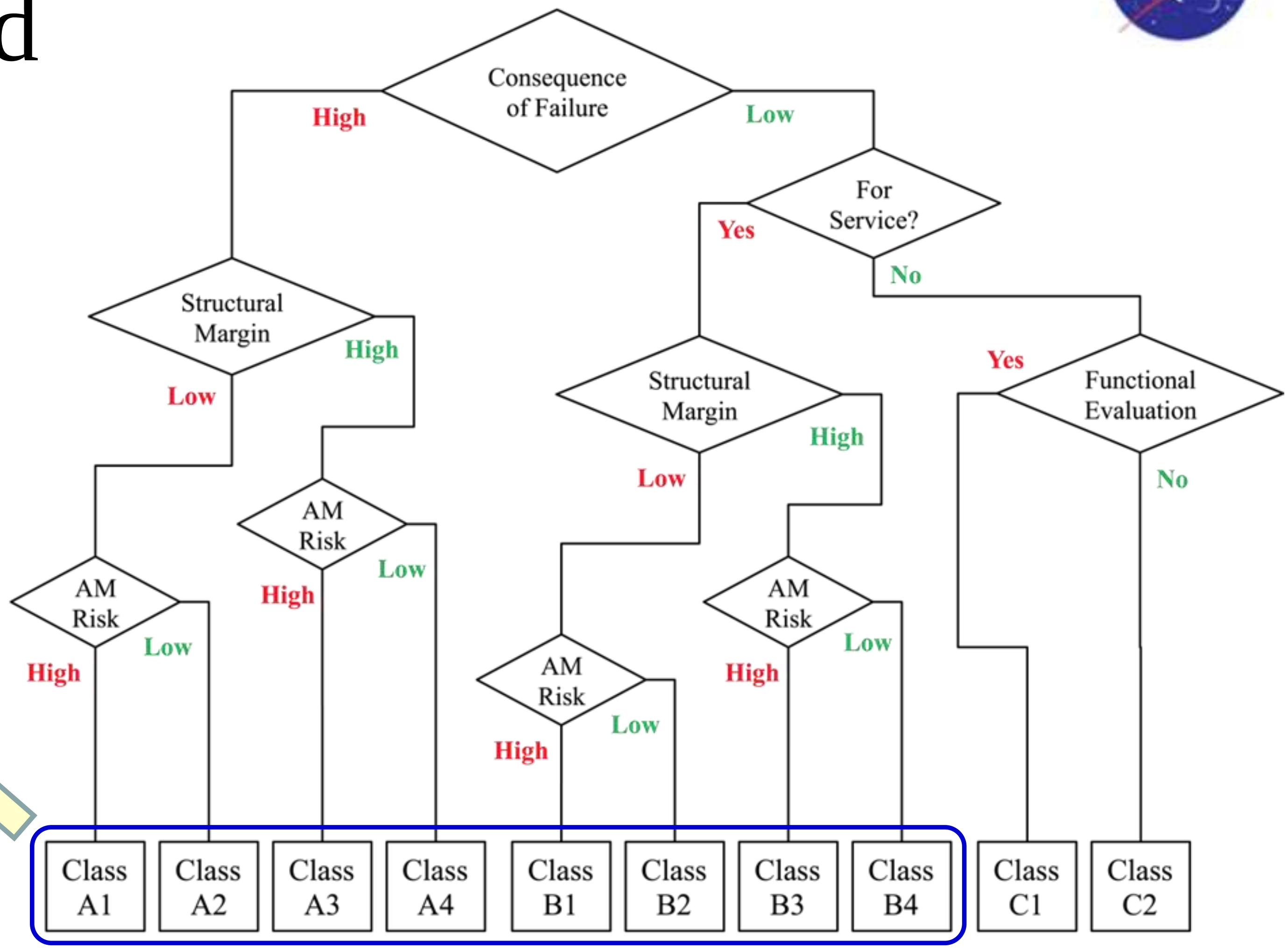
www.nasa.gov

NESC tech bulletin

https://www.nasa.gov/sites/default/files/atoms/files/nesc_tb_17-01_development_of_nasa_standards_for_enabling_certification_of_am_parts.pdf

Background

Comprehensive NDE required for surface and volumetric defects



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

Acknowledgments

- Eric Burke & James Walker : NASA-OSMA NDE Program AM Foundational Effort
- Doug Wells: MSFC AM Spaceflight Hardware Quality Document
- Steve James (Aerojet Rocketdyne): ASTM Round Robin Testing
- Bill Prosser & Ken Hodges: NESC NDE Technical Discipline Team
- Risk Russell: NESC Materials Fellow
- Arthur Brown: NASA MSFC Inconel® 718 product variability
- Tracie Prater: Plastic AM parts for Nonlinear Resonant Spectroscopy (NRUS) evaluation
- ASTM WK47031 Collaboration Area: NDE subject matters experts
- … and many more who have contribution their time and/or their company's resources

Back-ups

OMB A-119

federal register

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

- Agencies must consult with voluntary consensus standards bodies, and must participate with such bodies in the development of voluntary consensus standards when consultation and participation is in the public interest
- If development of a standard is impractical or infeasible, the agency must develop an explanation of the reasons for impracticality and the steps necessary to overcome the impracticality
- Any standards developed must be necessarily non-duplicative and noncompetitive

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

America Makes & ANSI AMSC Working Groups

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

Process and Materials WG*

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

Future State: Left to Right Enabling Commercialized AM products

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

Chemistry
Cleanliness
Feed stock characterization
Safety & Training
OEM process & control

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

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

Post-Processing SG
Meets: Every other Tuesday, 1-2 pm Eastern, beginning May 10, 2016
Leader: Patrick Ryan, L5 Management

Heat Treat
HIP
Surface finishing
Machining
Removal of Support Material

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

Mechanical properties
Quality control
Component testing
Component certification
Bio-compatibility
Chemistry
Design allowables
Cleanliness
Microstructure

America Makes
National Additive Manufacturing Innovation Institute

ANSI
American National Standards Institute

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

Design WG

Meets: Every other Tuesday, 10-11:30 am Eastern, beginning May 10, 2016

Co-chairs: John Schmelzle, NAVAIR, and Jayanthi Parthasarathy, MedCAD

Input (Design guides, Design intent)

Designing parts (Design tools, Simulation and modeling, Design for assemblies, Design for printed electronics, Design for bio)

Design documentation (Neutral build file, Product definition data sets)

Validation (of design and models)

Maintenance WG

Meets: Every other Monday 2-3:30 pm Eastern, beginning May 16, 2016

Co-chairs: David Coyle, NAVSUP WSS, and Michele Hanna, Lockheed Martin

Scope: Maintenance of parts and machines

Standard repair procedures for parts and tooling

Standard inspection processes

Model based inspection

Standards for tracking maintenance operations

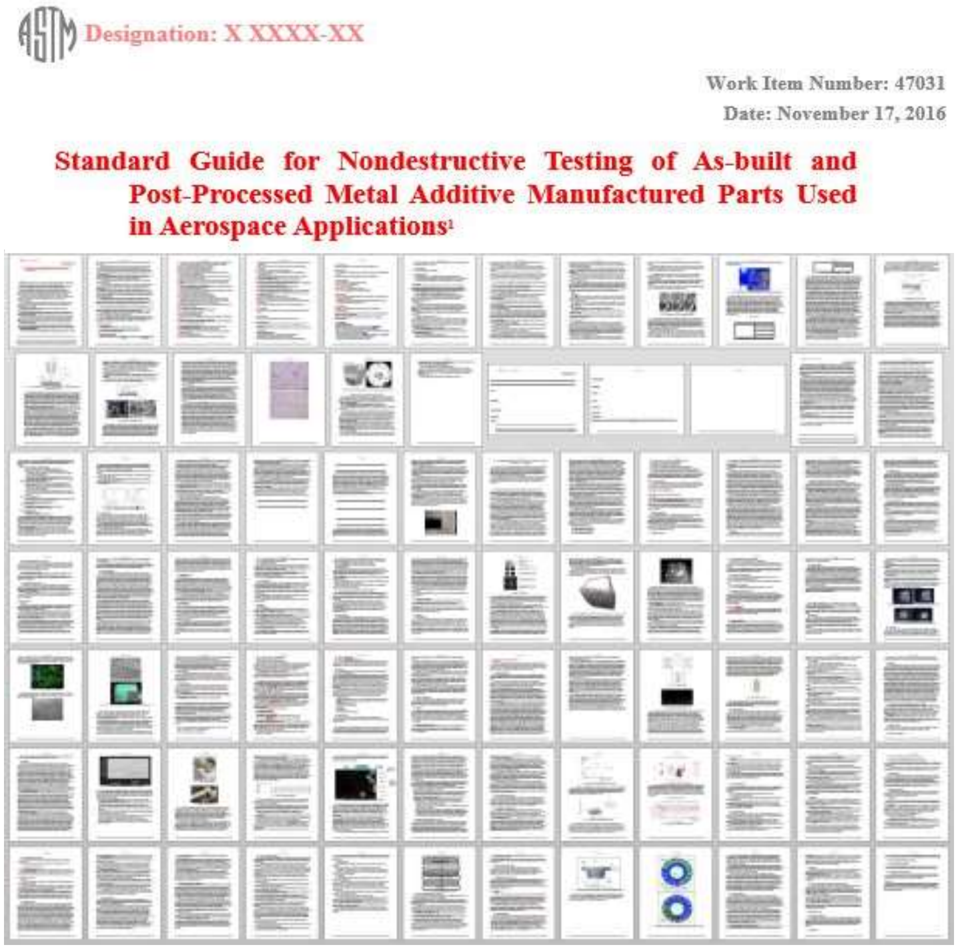
Workforce development

Cybersecurity

ASME ISO ASTM INTERNATIONAL SAE AWS

ASTM Subcommittee E07.10 on Specialized NDT Methods

CT, MET, PCRT, PT, RT, TT, and UT sections


Designation: X XXXX-XX

Work Item Number: 47031
Date: November 17, 2016

Standard Guide for Nondestructive Testing of As-built and Post-Processed Metal Additive Manufactured Parts Used in Aerospace Applications[1]

In Ballot

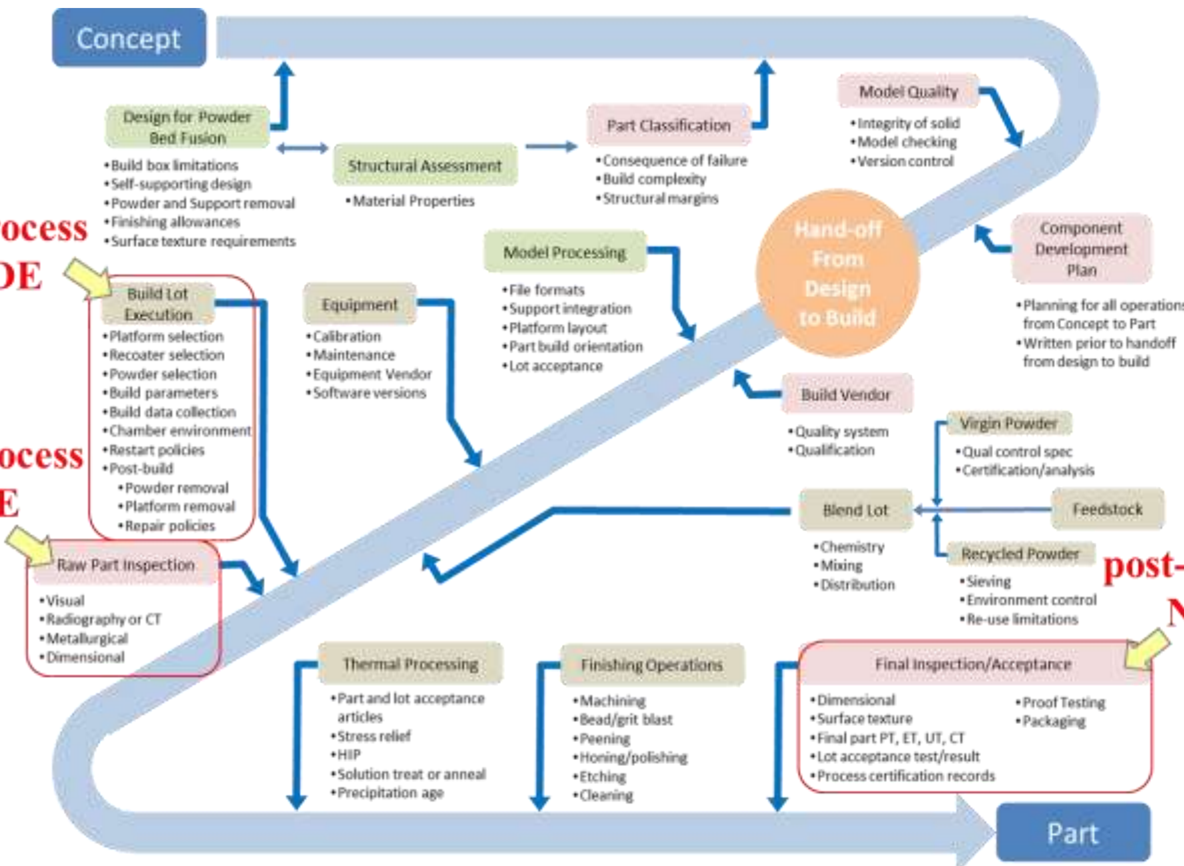
- Defect type & part complexity determine NDE selection
- Process method determines defects determines NDE

Future Standards for NDT of AM Aerospace Materials

- New Guide for *In-situ Monitoring of Additively Manufactured Parts used in Aerospace Applications* (**POC: Surendra Singh/Honeywell)**

Singh: new E07 standard → in-process NDE

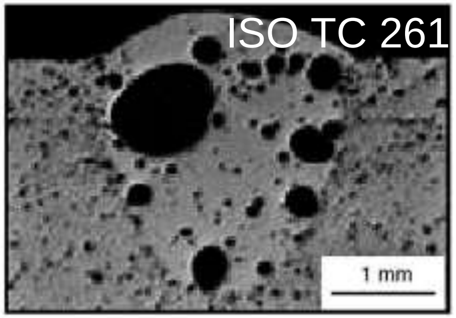
Waller: WK47031 → post-process NDE



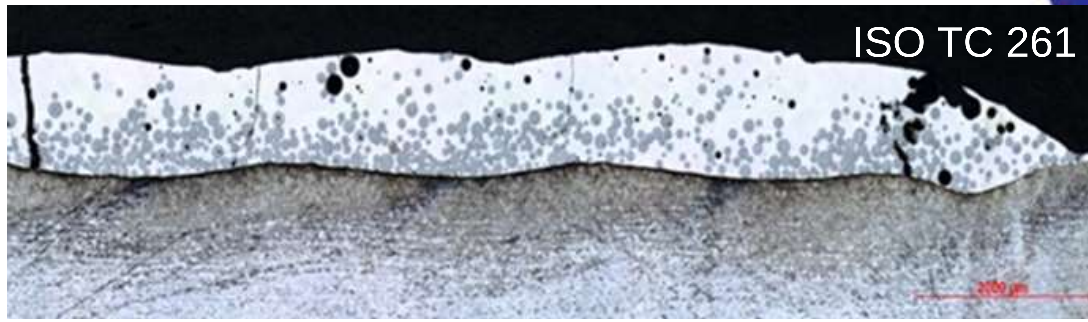
post-process NDT ← Waller: WK47031

- 1/23/17: E07.10 motion to register a new standard and assign jurisdiction passed

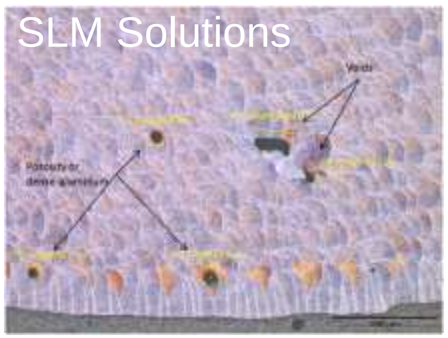
Typical PBF and DED Defects



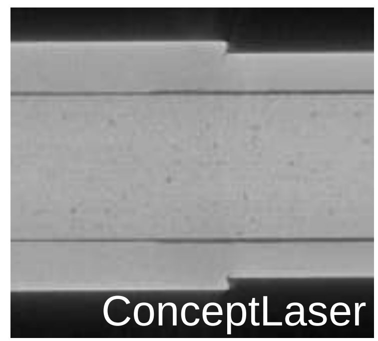
PBF Porosity

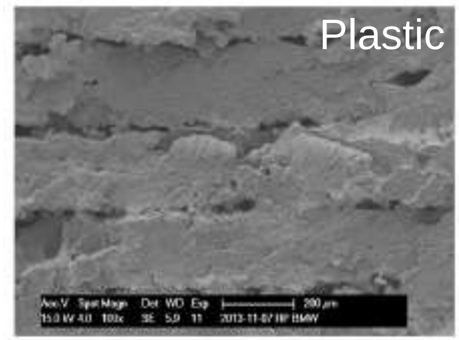


DED Porosity



Porosity and Voids





Voids

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

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

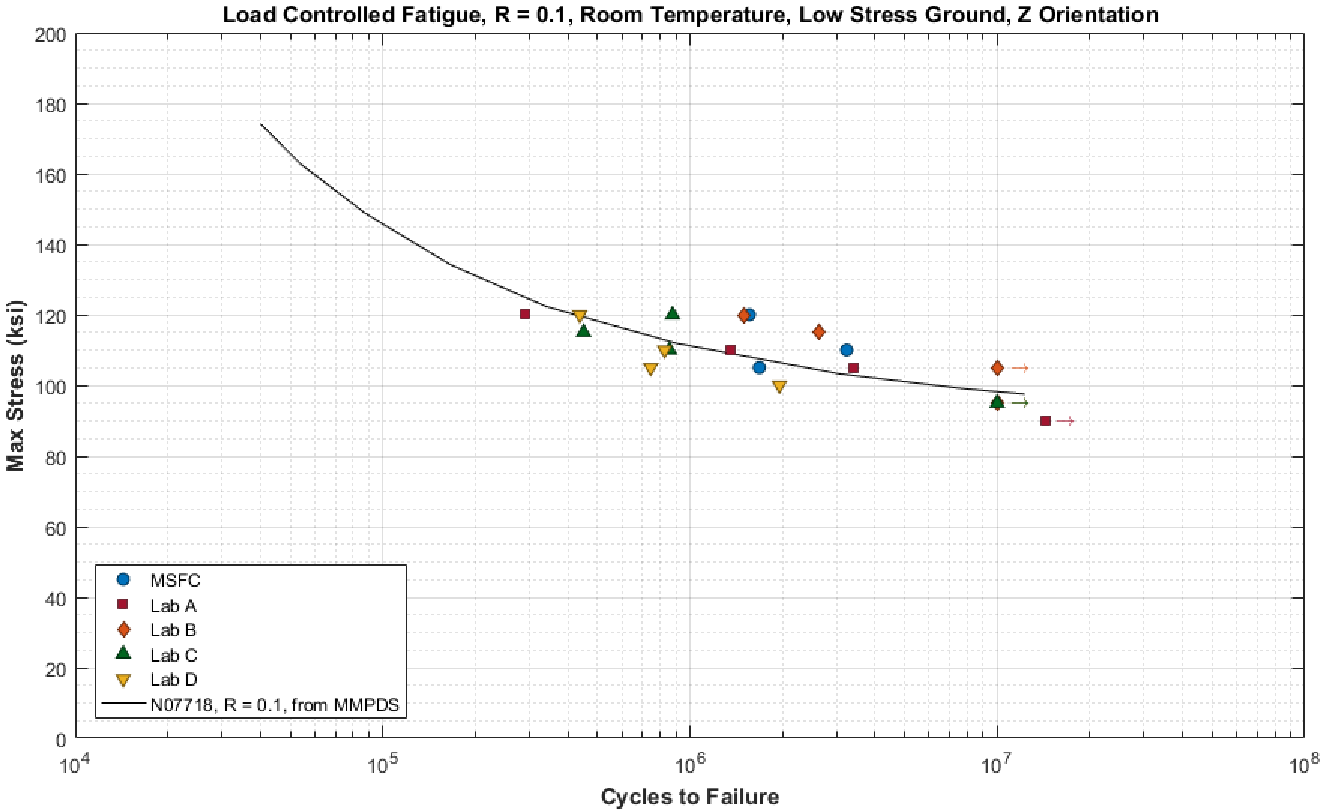
lack of fusion (LOF) *n*—flaws caused by incomplete melting and cohesion between the deposited metal and previously deposited metal.

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

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

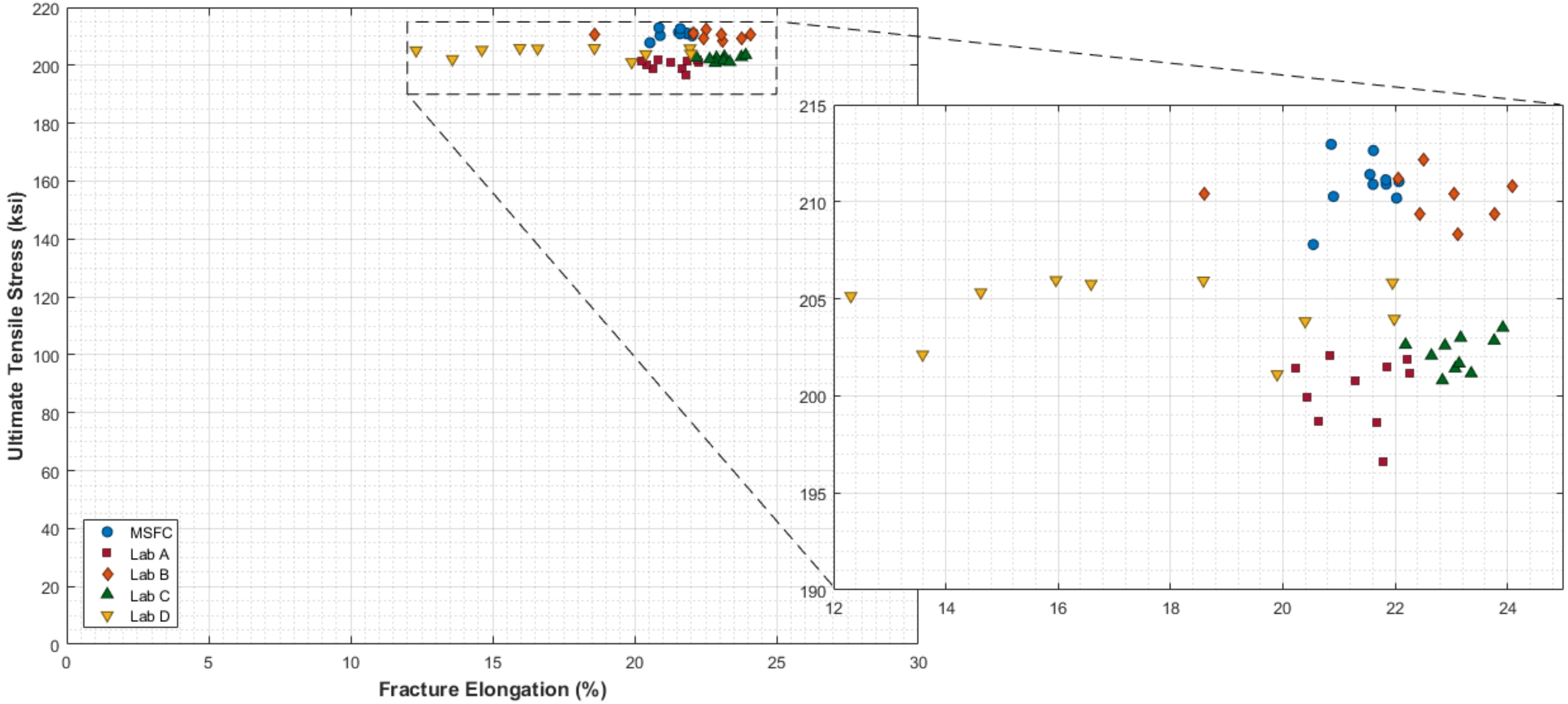
Round Robin: Low Cycle Fatigue

- 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.



NASA OSMA QA of AM Workshop at JPL - NDE Break-out Session findings

NDE Discussion Points

What is the role of QA? What should be presented at the PDR/CDR?

NDE of As-Built and Post-Processed AM Hardware

- Flaw identification (**Defect Catalog**)
  - Must specify process type relative to defect type (for example, DED vs. PBF flaws)
  - U.S. and E.U. terminologies differ
- **Effect-of-defect studies** (on sacrificial samples)
  - Effect of large/small defects
  - Effect of flaw homogeneity/distribution
  - Effect of HIPing, heat treatment on flaw size and detection
- **Develop acceptance criteria** (NDE capabilities)
  - Need to engage fracture & fatigue SMEs and answer what is the critical or important flaw type
    - Joint AM/NDE/fracture and fatigue push
    - Define criticality of defect (design, location, and type)
  - Define acceptance levels (flaw type, size and distribution)
  - Part-specific vs. universal acceptance criteria?
  - Proprietary company specific criteria
- **What is the NDE capability at the critical flaw size for high value, fracture critical parts?**
  - Are current physical reference standards adequate?
  - How statistically significant does the NDE need to be?
- **NDE of first articles, versus reference or witness coupons, production parts, and spares**

- Key development areas, challenges and promising work captured
- NESC NDE TDT briefed on 10/26/17; OSMA NDE Program briefed

- **Bulk Defects**
  - **Lack of Fusion**
    - **Horizontal Lack of Fusion Defect**
      - Insufficient Power
      - Laser Attenuation
      - Spatter
    - **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

- The list to the left is color coded to show the know 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

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

Any Questions?

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