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

INTENDED AUDIENCE & LEARNING OBJECTIVES

- 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.

Session I Schedule (sample, revise as needed)

Session II Schedule (sample, revise as needed)

FOCUS

- 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?!

BACKGROUND

- 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)

Metallic Aerospace AM Parts – Example 1

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.

28-element Inconel® 625 fuel injector built using an laser powder bed fusion (L-PBF) process

https://www.nasa.gov/press/2014/august/sparks-fly-as-nasa-pushes-the-limits-of-3-d-printing-technology/

Metallic Aerospace AM Parts – Example 2

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."

SpaceX SuperDraco combustion chamber for Dragon V2 made from Inconel using the DMLS process

http://www.spacex.com/press/2014/05/27/spacex-completes-qualification-testing-superdraco-thruster

Metallic Aerospace AM Parts – Example 3

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× higher durability vs. conventional manufacturing.

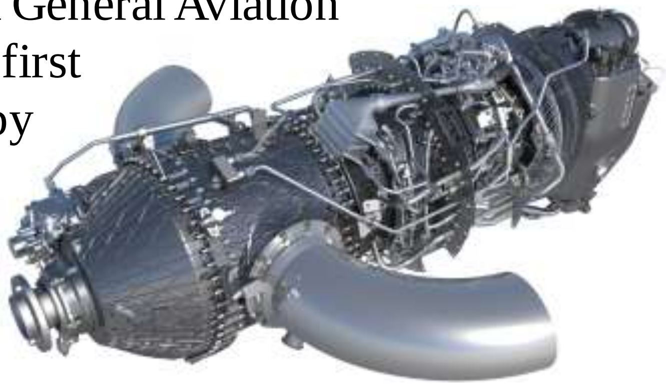
GE Leap Engine fuel nozzle. CoCr material fabricated by direct metal laser melting (DMLM), GE's acronym for DMLS, SLM, etc.

"*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*."

http://www.madeinalabama.com/2015/06/ge-aviation-readies-first-3-d-printed-jet-engine-nozzle/

Metallic Aerospace AM Parts – Example 4

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.



GE advanced turboprop (ATP) engine: AM has allowed designers to consolidate 855 parts into just 12, resulting in reduced weight and improved fuel efficiency.

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.

https://www.ge.com/reports/mad-props-3d-printed-airplane-engine-will-run-year/

Metallic Aerospace AM Parts – Example 5

AEROJET ROCKETDYNE 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.*"

A technician for NASA's RS-25 prime contractor Aerojet Rocketdyne exhibits the pogo accumulator assembly, NASA's largest 3D-printed rocket engine component tested in the restart of RS-25 production.

https://www.nasa.gov/exploration/systems/sls/nasa-tests-3-d-printed-rocket-part-to-reduce-future-sls-engine-costs

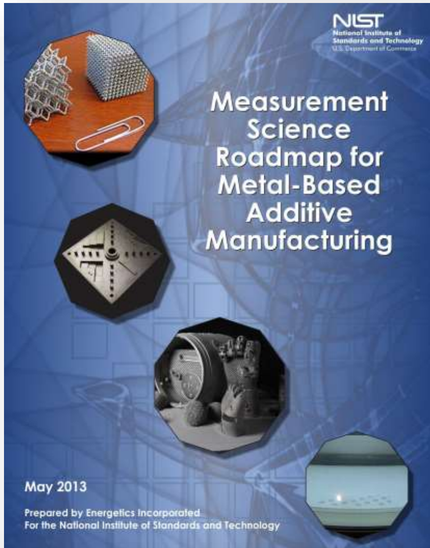
BACKGROUND

- 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

split into 2 documents

Key NASA AM Qualification & Certification Documents (cont.)


EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

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

July 2015


MEASUREMENT SYSTEM IDENTIFICATION METRIC/SI (ENGLISH) UNITS

National Aeronautics and Space Administration

MSFC-STD-3716
BASELINE
EFFECTIVE DATE: October 18, 2017

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

EM20

MSFC TECHNICAL STANDARD

STANDARD FOR ADDITIVELY MANUFACTURED SPACEFLIGHT HARDWARE BY LASER POWDER BED FUSION IN METALS

Approved for Public Release; Distribution is Unlimited

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

released
October 18, 2017


MEASUREMENT SYSTEM IDENTIFICATION METRIC/SI (ENGLISH) UNITS

National Aeronautics and Space Administration

MSFC-SPEC-3717
BASELINE
EFFECTIVE DATE: October 18, 2017

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

EM20

MSFC TECHNICAL STANDARD

SPECIFICATION FOR CONTROL AND QUALIFICATION OF LASER POWDER BED FUSION METALLURGICAL PROCESSES

Approved for Public Release; Distribution is Unlimited

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

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

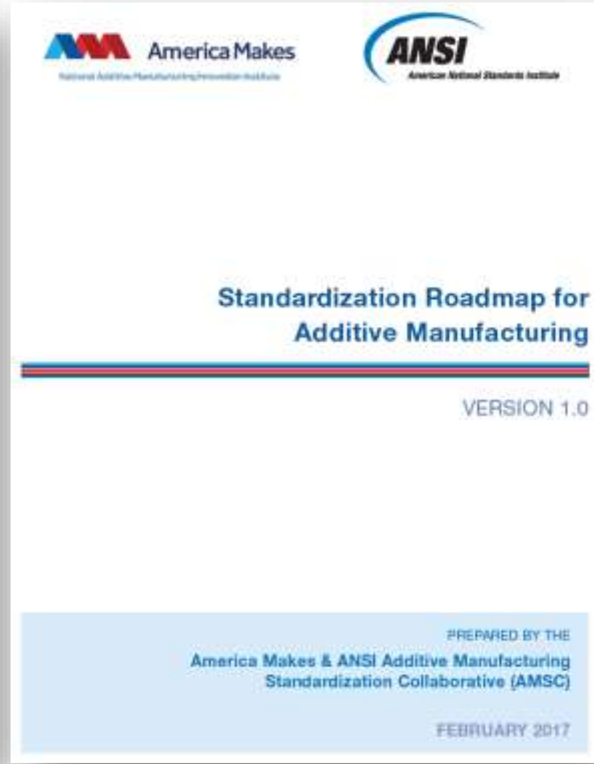
For information contact the NESC at www.nesc.nasa.gov

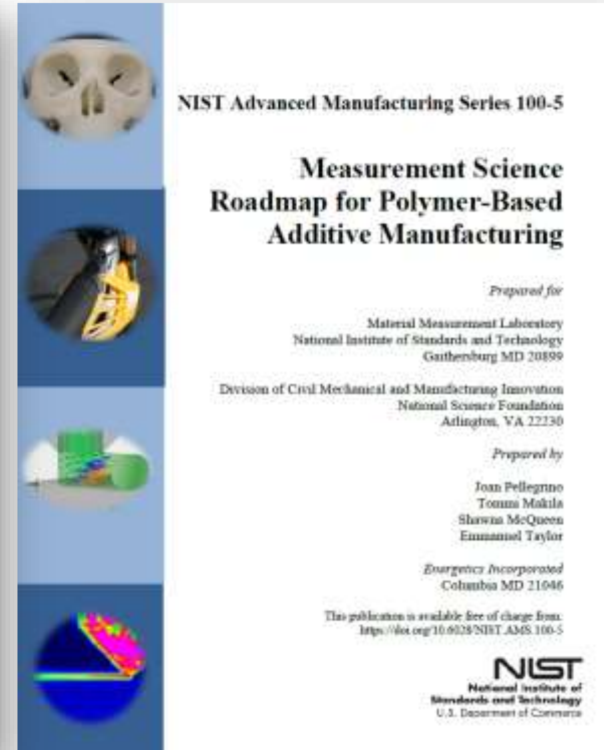
www.nasa.gov

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

Other Key AM Documents (Roadmaps) (cont.)



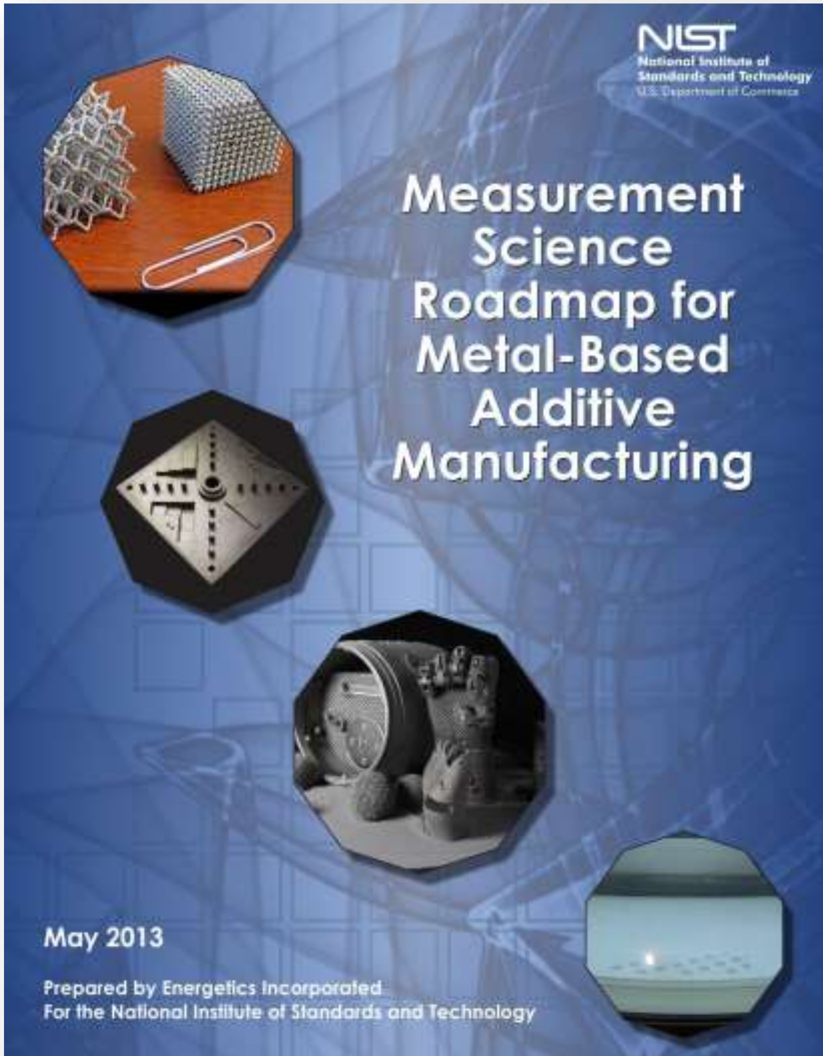


December 2015 ✓

February 2017 ✓

December 2016 ✗

✓ = discussed in this course



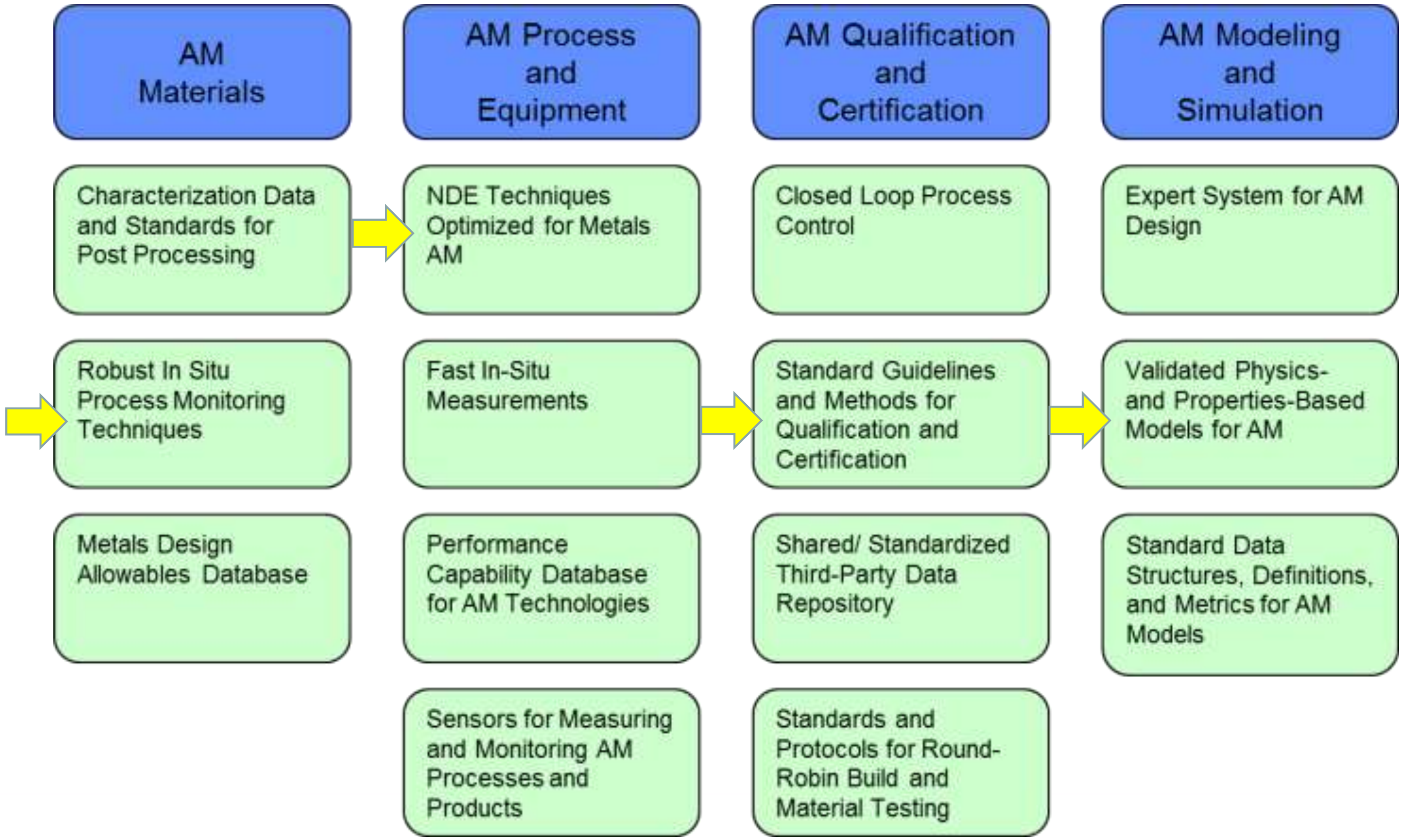
Contact: *Kevin Jurrens (NIST)*

- 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:
  - Matt Showalter, GSFC
  - Karen Taminger, LaRC
  - Gary Wainwright, LaRC
  - Nancy Tolliver, MSFC

https://www.nist.gov/sites/default/files/documents/el/isd/NISTAdd_Mfg_Report_FINAL-2.pdf

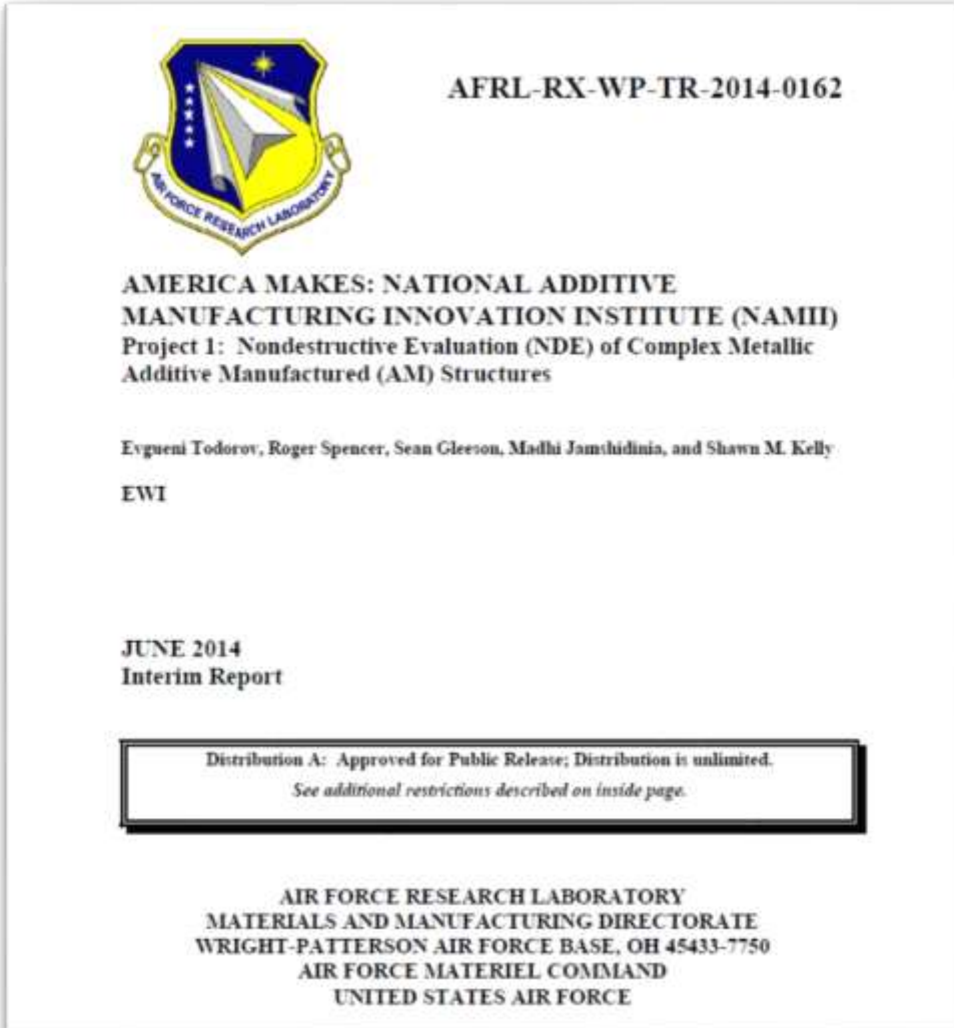
NIST Roadmap for Metal-Based AM

Important Technology and Measurement Challenges for AM



- Cross-cutting needs for NDE
- Highly influential in development of 2014 NASA State-of-the-Discipline Report

USAF/AFRL-RX-WP-TR-2014-0162 NDE of Complex AM Structures



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

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See additional restrictions described on inside page.

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

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.

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.831.6412&rep=rep1&type=pdf

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):

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.

USAF/AFRL-RX-WP-TR-2014-0162 NDE of Complex AM Structures

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

⇨ Optical Method (OM)

⇨ parts where liquid/gas leak tightness reqd.

⇨ post-machining reqd., line of sight issues

⇨ ASTM E2534

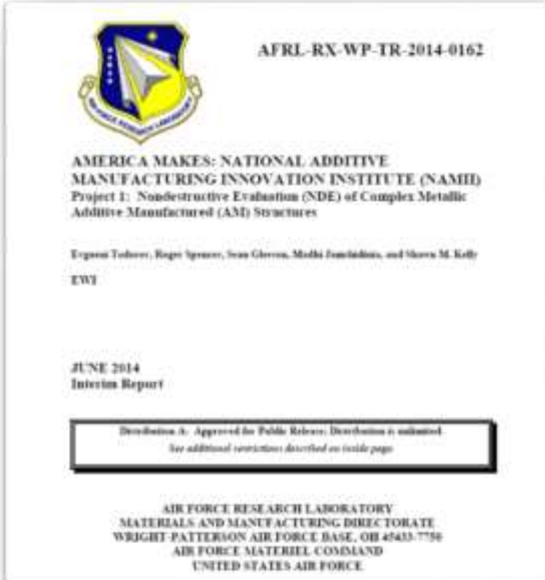
⇨ correlate R, σ with mechanical props

⇨ correlate σ with microstructure and residual stresses

⇨ measurement of compressive elastic stresses by peening

NDE Technique	Common Acronym	Material and Flaw Types Detected	Surface or Interior	Global Screening or Detect Location
Array Eddy Current Testing	AEC	In electrically conductive material any condition and/or defect affecting electrical conductivity, magnetic permeability and/or sensor-part juxtaposition	Surface and slightly subsurface	Detects and images location
Phase Array Ultrasonic Testing	PAUT	In any solid material, any condition and/or defect affecting sound attenuation, propagation, acoustic velocity and/or sensor-part juxtaposition.	Surface and subsurface	Detects and images location
Ultrasonic Testing	UT	In any solid material, any condition and/or defect affecting sound attenuation, propagation, acoustic velocity and/or sensor-part juxtaposition.	Surface and subsurface	Detects location
Radiographic Testing	RT	In any solid material, any condition and/or defect affecting X-ray absorption.	Surface and subsurface	Detects and images location
X-Ray Computed Tomography	X-Ray CT	In any solid material, any condition and/or defect affecting X-ray absorption.	Surface and subsurface	Detects and images location
Microfocus X-Ray Computed Tomography	X-ray MicroFCT	In any solid material, any condition and/or defect affecting X-ray absorption.	Surface and subsurface	Detects and images location

- fast scanning of large areas with minimal sweeps
- surface adaptive UT for complex shapes, use advanced time reversal focusing algorithms
- influenced by microstructure, grain size, anisotropy
- inspection of Group 1 and 2, and limited application for 3
- broad in-house NASA capability


AFRL-RX-WP-TR-2014-0162

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Project 1: Nondestructive Evaluation (NDE) of Complex Metallic Additive Manufactured (AM) Structures

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

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

§ 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.

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

Kenneth L. Hodges
Goddard Space Flight Center, Greenbelt, Maryland

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Prepared for

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia

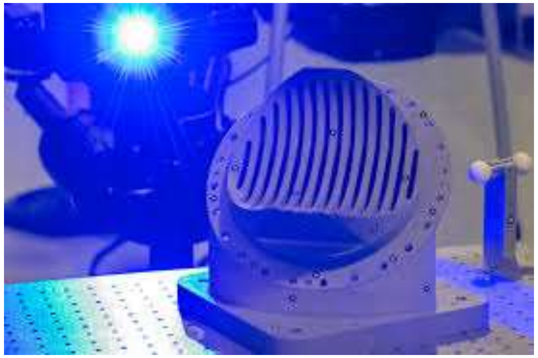
November 2014

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

- NASA Agency additive manufacturing efforts 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.

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140016447.pdf

NASA Agency & Prime Contractor Activity, ca. 2014



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 fight testing

28-element Inconel 625 fuel injector

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

NASA Agency & Prime Contractor Activity, Recent

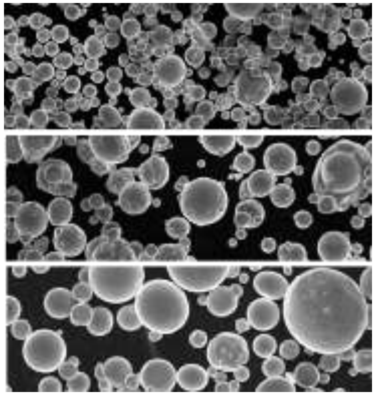
JPL Mars Science Laboratory Cold Encoder Shaft fabricated by gradient additive processes

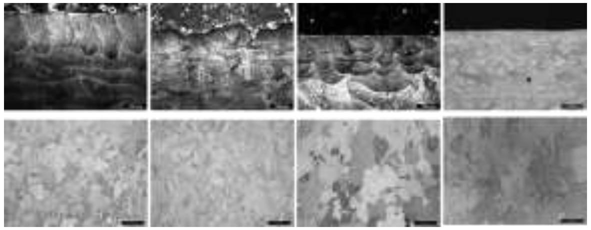
MSFC copper combustion chamber liner for extreme temperature and pressure applications

NASA-sponsored 3-D Printed Habitat Challenge Design Competition

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

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 AM Structural Integrity Initiative (AMSII)

- 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).

Initial Evaluation	Steven J. Gentz
	April 21, 2016

Additive Manufacturing Structural Integrity Initiative (AMSII) Project Oversight and Support

Steven J. Gentz

April 21, 2016

This document contains SBU, ITAR, and/or proprietary data. Restricted distribution to NESC and designated team members until approved by the NRB. This is for status only and does not represent complete engineering analysis. 2

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_3H_6).

(work performed under a 2015 NASA Space Technology Mission Directorate Space Act Agreement)

Image courtesy of Vector Space System

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.

NASA TECHNICAL STANDARD

National Aeronautics and Space Administration
Washington, DC 20546-0001

NASA-STD-5009

Approved: 04-07-2008
Superseding NASA-STD-(I)-5009 and MSFC-STD-1249

NONDESTRUCTIVE EVALUATION REQUIREMENTS FOR FRACTURE-CRITICAL METALLIC COMPONENTS

MEASUREMENT SYSTEM IDENTIFICATION:
METRIC (INCH-POUND)

APPROVED FOR PUBLIC RELEASE—DISTRIBUTION IS UNLIMITED

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.)

Système International (SI) Units (millimeters)

Crack Location	Part Thickness, t	Crack Type	Crack Dimension, a*	Crack Dimension, c*
		Eddy Current NDE		
Open Surface	t ≤ 1.27 t > 1.27	Through PTC[1]	t 0.51 1.27	1.27 2.54 1.27
Edge or Hole	t ≤ 1.91 t > 1.91	Through Corner	t 1.91	2.54 1.91
		Penetrant NDE		
Open Surface	t ≤ 1.27 1.27<t <1.91 t > 1.91	Through Through PTC	t t 0.64 1.91	2.54 3.81 – t 3.18 1.91
Edge or Hole	t ≤ 2.54 t > 2.54	Through Corner	t 2.54	3.81 3.81
		Magnetic Particle NDE		
Open Surface	t ≤ 1.91 t > 1.91	Through PTC	t 0.97 1.91	3.18 4.78 3.18
Edge or Hole	t ≤ 1.91 t > 1.91	Through Corner	t 1.91	6.35 6.35
		Radiographic NDE		
Open Surface	t ≤2.72 t > 2.72	PTC PTC Embedded	0.7t 0.7t 2a=0.7t	1.91 0.7t 0.7t
		Ultrasonic NDE Comparable to a Class A Quality Level (ASTM-E-2375)		
Open Surface	t ≥ 2.54	PTC Embedded**	0.76 1.65 0.43 0.99	3.81 1.65 2.21 0.99

[1] PTC – Partly through crack (Surface Crack)
* See figure 1 for definitions of "a" and "c" for different geometries.
** Equivalent area is acceptable, ASTM-E-2375 Class A.

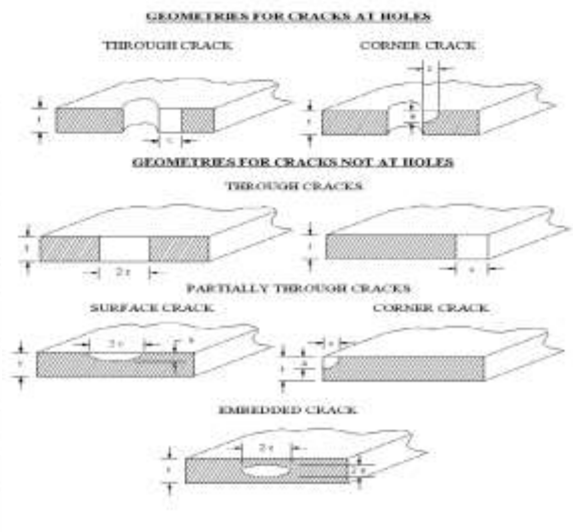


Figure 1—Assumed Flaw Geometries

§ 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 — 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
- 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
- last • Develop NDE-based qualification and certification protocols for flight hardware (screen out critical defects)

somewhere in the middle


CAMM Consortium for Additive Manufacturing Materials

Strategic Roadmap for the Next Generation of Additive Manufacturing Materials

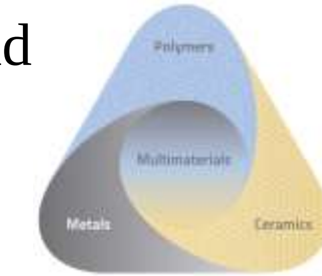
Prepared by: PennState CIMP-3D

NEXIGHT GROUP

December 2015

http://www.cimp-3d.org/documents/camm_roadmap.pdf

Contact: *PSU CIMP-3D*

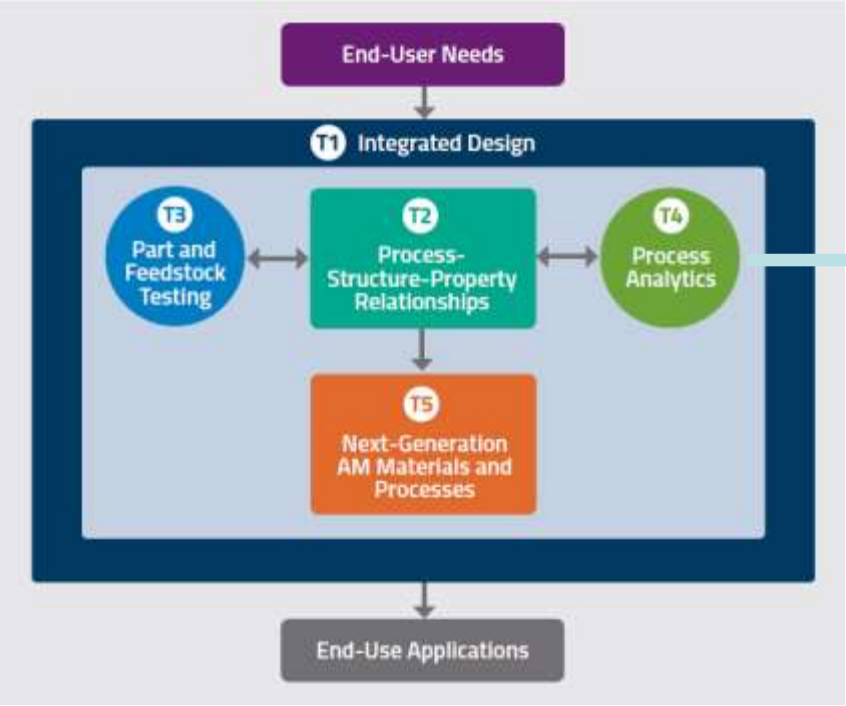


- Covers metal, polymer, and ceramic AM processing.
- AM applications rely on feed stocks which have not been optimized for AM.
- Industry must develop new materials and feedstock's specifically tailored for AM to realize advantages in next generation applications and designs.
- Focuses on basic research (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.

CAMM Roadmap for Metal-Based AM (2015)

<u>CAMM Thrust Areas:</u>

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



repeated melting and solidification of build layers

↓

loss of net shape, crack formation, or delamination

↓

neutron diffraction NDE

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.[§]

[§] Wu, A., Donald, S., Brown, W., Kumar, M., Gallegos, G. F., King, W. E., "An Experimental Investigation into Additive Manufacturing-Induced Residual Stresses in 316L Stainless Steel," *Metallurg. Matls. Trans. A* **45(13)** (2014): 6260-6270.

CAMM Roadmap for Metal-Based AM / Processing Methods

AM PROCESS CATEGORY[1]	AM PROCESS TYPE	MATERIAL: METALS	MATERIAL: POLYMERS	MATERIAL: CERAMICS	BINDER OR FUSION MECHANISM: LASER BEAM	BINDER OR FUSION MECHANISM: ELECTRON BEAM	BINDER OR FUSION MECHANISM: PLASMA ARC	BINDER OR FUSION MECHANISM: ULTRAVIOLET	BINDER OR FUSION MECHANISM: LIQUID BINDING AGENT	BINDER OR FUSION MECHANISM: ULTRASONIC	BINDER OR FUSION MECHANISM: OTHER HEAT / POST-PROCESSING	FEEDSTOCK FORM: POWDER	FEEDSTOCK FORM: FILAMENT	FEEDSTOCK FORM: RESIN	FEEDSTOCK FORM: SHEET
Binder Jetting	---	●	●	●					●		●	●		●	
Directed Energy Deposition	Blown Powder	●	●	●	●						●	●			
	Ion Fusion Formation	●					●				●		●		
	Electron Beam Direct Manufacturing	●				●					●		●		
Material Extrusion	Fused Deposition Modeling		●								●		●		
	Multiphase Jet Solidification	●	●	●							●	●	●		
Material Jetting	---		●					●						●	
Powder Bed Fusion	Laser Sintering		●	●	●						●	●		●	
	Laser Melting	●			●						●	●			
	Electron Beam Melting	●				●					●	●			
Sheet Lamination	Laminated Object Manufacturing	●	●	●							●	●			●
	Ultrasonic Consolidation	●								●	●				●
Vat Photo-polymerization	---		●	●					●		●	●		●	

= this course

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.

Quality Assurance of AM Hardware from an NDE Perspective (2016)

NASA QUALITY ASSURANCE IN ADDITIVE MANUFACTURING (AM) –

A WORKSHOP ON ASSURING AM PRODUCT INTEGRITY

When: October 11-12, 2016
Where: Beckman Auditorium, California Institute of Technology, Pasadena CA

For QLF members: please register at the QLF website (https://qlf.jpl.nasa.gov), click on "Events"
For non-QLF members: please email Diana Shellman at diana.l.shellman@jpl.nasa.gov, 818-393-0745

Jointly sponsored by NASA Quality Leadership Forum and ASQ Collaboration on Quality in the Space and Defense Industries

Breakout sessions held for NDE, Supplier/OEM Auditing and Qualification, Powder Quality, and Industry/Academic Partnerships

Quality Assurance of AM Hardware from an NDE Perspective (2016)

- 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.

Challenges in NDE Developmental 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**

Promising Directions in NDE Developmental Areas

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)

ASTM F42 / ISO TC 261 JG59 Efforts

Causes

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

(Process)

Defects (DED & PBF)

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

(Structure)

As-Processed Failure Mode

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

(Property)

Defects – Effect of Process [§]

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	X	X		
	Porosity		X	X	
	Incomplete fusion			X	
	Lack of geometrical accuracy/steps in part	X	X		
	Undercuts			X	
	Non-uniform weld bead and fusion characteristic			X	
	Hole or void		X	X	
	Non-metallic inclusions		X	X	
	Cracking		X	X	
PBF	**Unconsolidated powder**				X
	Lack of geometrical accuracy/steps in part	X	X		
	Reduced mechanical properties	X			
	Inclusions		X	X	
	Void		X	X	
	Layer				X
	Cross layer				X
	Porosity		X	X	
	Poor surface finish	X	X		
	Trapped powder				X

Develop new NDE methods

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

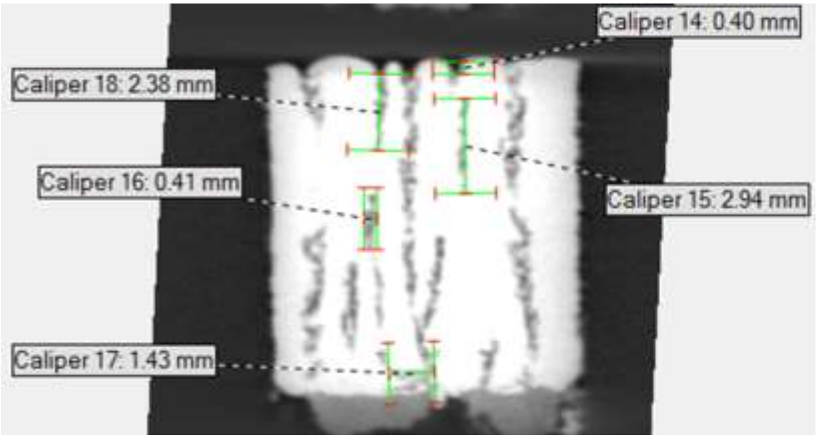
Note: DED = Directed Energy Deposition., PBF = Powder Bed Fusion

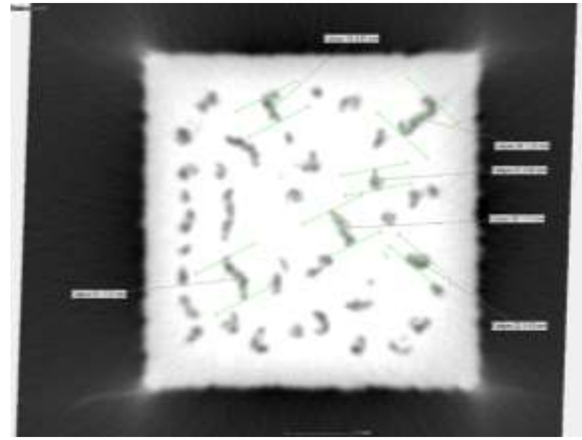
Typical AM Defects and Causes

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

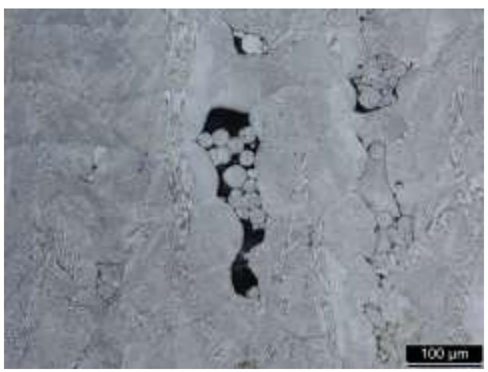
Courtesy of AMAZE an FP7 EU project http://www.amaze-project.eu/

Typical PBF Defects of Interest

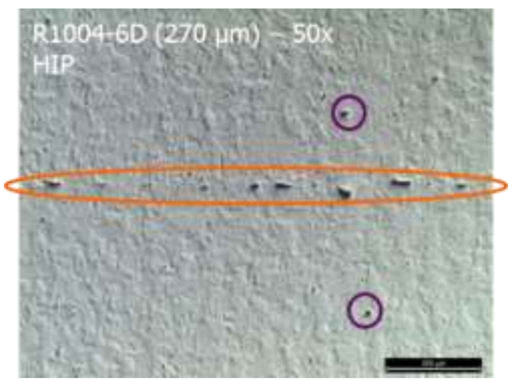




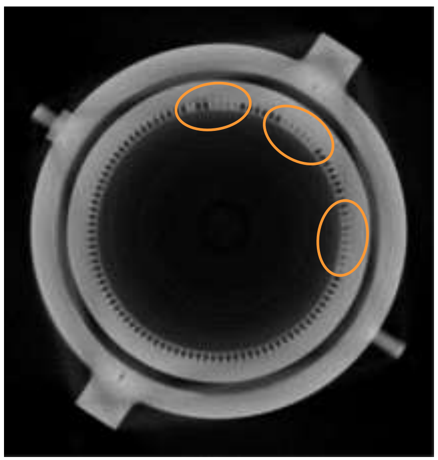
Cross layer



Lack of Fusion (LOF)



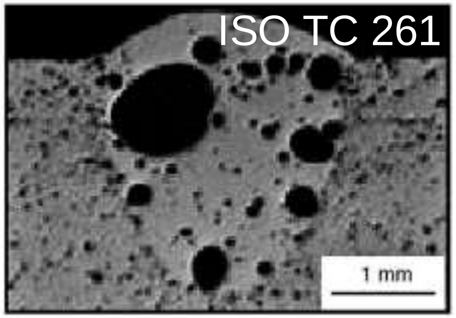
Layer



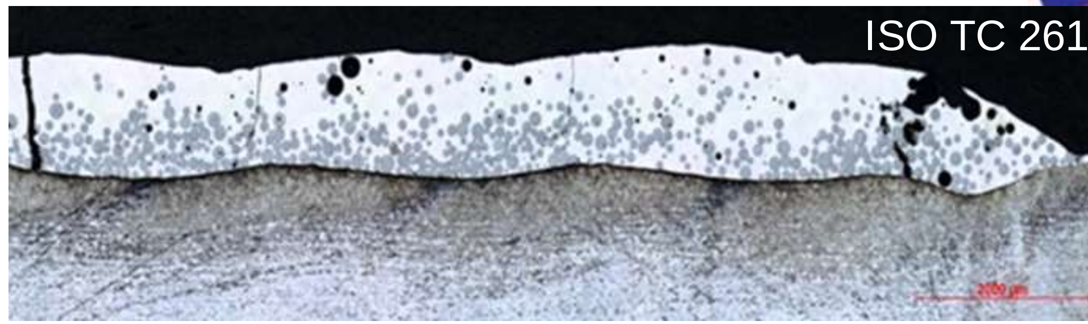
Trapped Powder

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

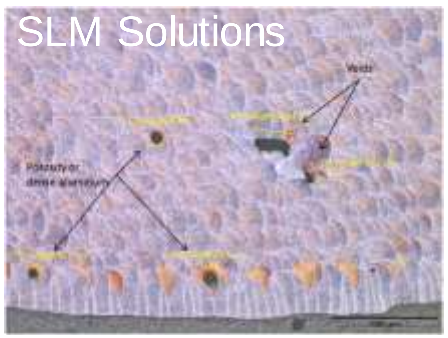
Typical PBF and DED Defects



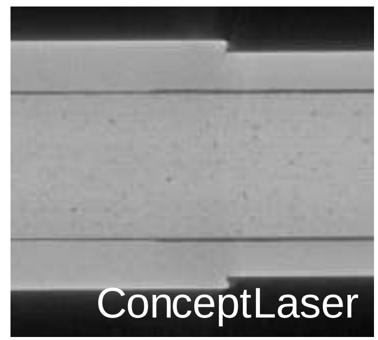
PBF Porosity

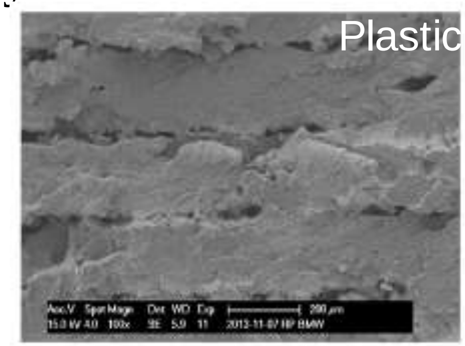


DED Porosity



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 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, *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.

Selection of NDE for Defect Detection[§]

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**	**ECT**	**MET**[B]	**PCRT**	**PT**	**TT**	**UT**	**AE**	**LT**	**ND**	**MT**	**VT**
Surface	X[C]	X[D]	X	...	X[D]	...	...	...	...	...	...	X
Porosity	X	X[D]	...	X	X[D]	...	X	...	...	...	...	X[E]
Cracking	X	X[D]	...	X	X[D]	X	X	X	X[F]	...	X	X
Lack of Fusion	X	X[D]	...	X	X[D]	X	X	X	...	...	X	...
Part Dimensions	X	...	X	...	...	...	...	...	...	...	...	...
Density[G]	X[H]	...	...	...	...	...	...	...	...	...	...	...
Inclusions	X[I]	X[D]	...	...	...	X	X	...	...	...	...	...
Discoloration	...	...	...	...	...	...	...	...	...	...	...	X
Residual Stress	...	X[D,J]	...	...	...	...	...	...	...	X	...	...
Hermetic Sealing	...	...	...	...	...	...	...	...	X[F]	...	...	...

[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] 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).

[D] Applicable if on surface.

[E] Macroscopic cracks only.

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

[G] Pycnometry (Archimedes principle).

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

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

[J] Residual stress can be assessed if resulting from surface post-processing (for example, peening).

[§] ASTM WK47031, new Draft Standard – Standard Guide for Nondestructive Testing of Metal Additively Manufactured Aerospace Parts After Build, ASTM International, West Conshohocken, PA (in balloting).

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

- 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

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

§ Brown, A., Jones, Z. Tilson, W., Classification, Effects, and Prevention of Build Defects in Powder-bed Fusion Printed Inconel 718, NASA Marshall Space Flight Center, 2016.

Defect Consequences §

- **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**

§ Brown, A., Jones, Z. Tilson, W., Classification, Effects, and Prevention of Build Defects in Powder-bed Fusion Printed Inconel 718, NASA Marshall Space Flight Center, 2016.

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?

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

- 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

Standards Development Organizations involved in AMSC

America Makes

ANSI American National Standards Institute

ASTM International	International Organization For Standardization
American Society of Mechanical Engineers	SAE International
American Welding Society	Institute of Electrical and Electronics Engineers
MITA Medical Imaging & Technology Alliance, a division of NEMA	Association for the Advancement of Medical Instrumentation
IPC – Association Connecting Electronics Industries	Metal Powder Industries Federation

America Makes Member Organizations (2014)

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*
Oxford Performance Materials*
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 Univeristy
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/ANSI Additive Manufacturing Standardization Collaborative

America Makes
National Additive Manufacturing Innovation Institute

ANSI
American National Standards Institute

- 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
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

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

③

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 & ANSI AMSC Working Groups

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

④

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)

⑤

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

America Makes & ANSI AMSC Findings

America Makes
National Additive Manufacturing Innovation Institute

ANSI
American National Standards Institute

- 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.

AMSC Sign-up Sheet

- Contact Jim McCabe of ANSI if interested in participating.

America Makes | ANSI American National Standards Institute

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 _x___

Precursor Materials WG ___

Process Control WG _x__

Post-processing WG ___

Finished Material Properties WG __

Qualification & Certification WG _x__

Nondestructive Evaluation WG _x__

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 HX5

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)	Scoring Values
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.	3 - critical; 2 - somewhat critical; 1 - not 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.	3 - project near completion; 2 - project underway; 1 - new project
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.	3 - low resource requirement; 2 - medium resource requirement; 1 - resource intensive
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.	3 - high return; 2 - medium return; 1 - low return

Score Rankings

Low Priority (a score of 4-6)

Medium Priority (a score of 7-9)

High Priority (a score of 10-12)

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

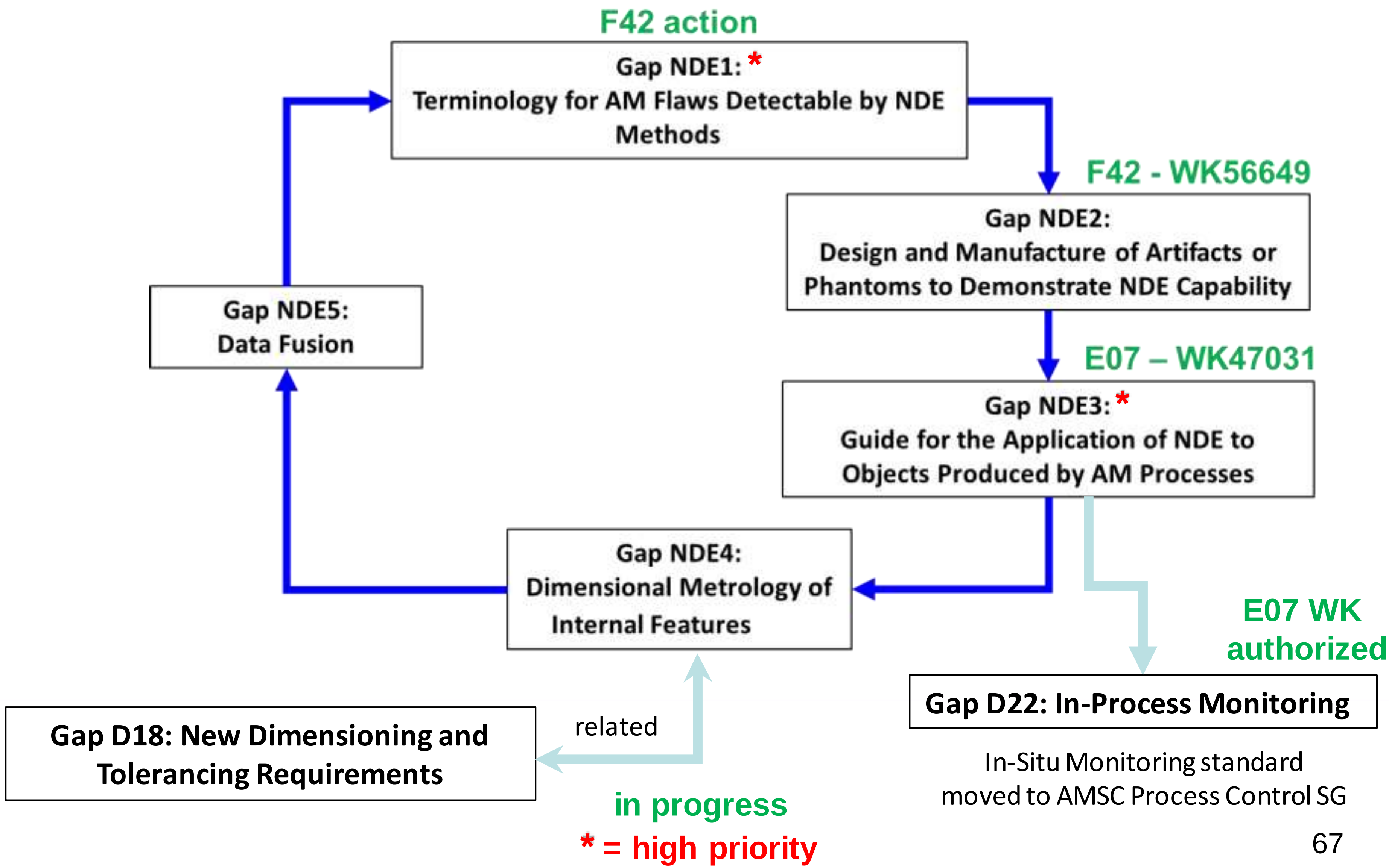
PREPARED BY THE
America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)

FEBRUARY 2017

AMSC NDE Working Group

- Led by Patrick Howard, GE Aviation
- 28 Members included Aerospace, Automotive and Medical Industries
- Mapping Started May 2016 – September2016
  - 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



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)

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, ET, MET, PCRT, PT, RT, TT, and UT)

Draft: WK56649 POC: S. James

F42

Standard Guide for
Intentionally Seeding Flaws in Additively Manufactured Parts

Draft prepared, F42 balloting planned

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 in E07.10 (IR, LUT, VIS, acoustic microscopy)

Draft: WKXXXX POC: TBD

E07

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

Future

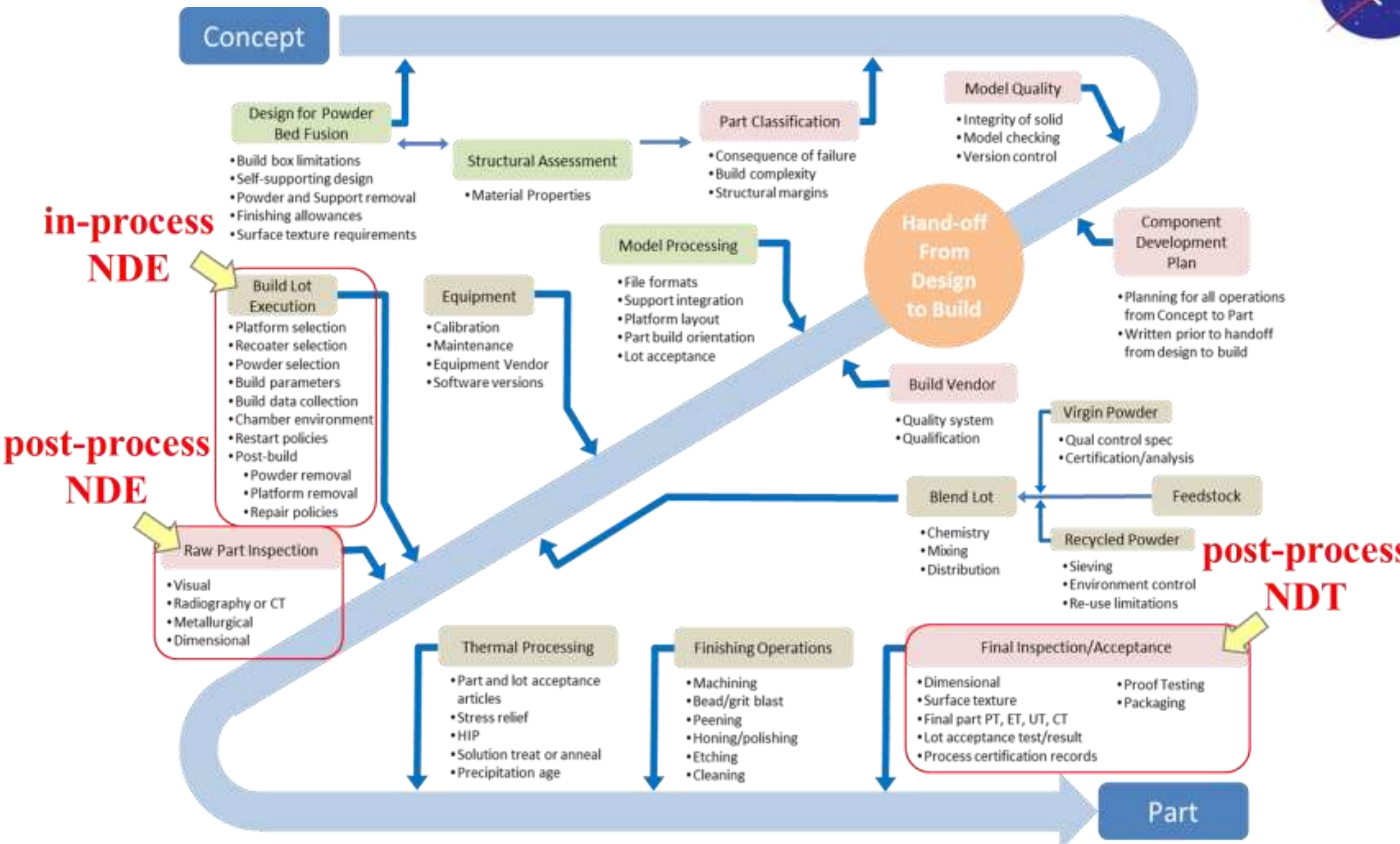
Draft: WKXXXX POC: TBD

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

NDE of AM Parts relative to Life Cycle



- In-process monitoring/optimization
- Post-manufacturing inspection
- Receiving inspection

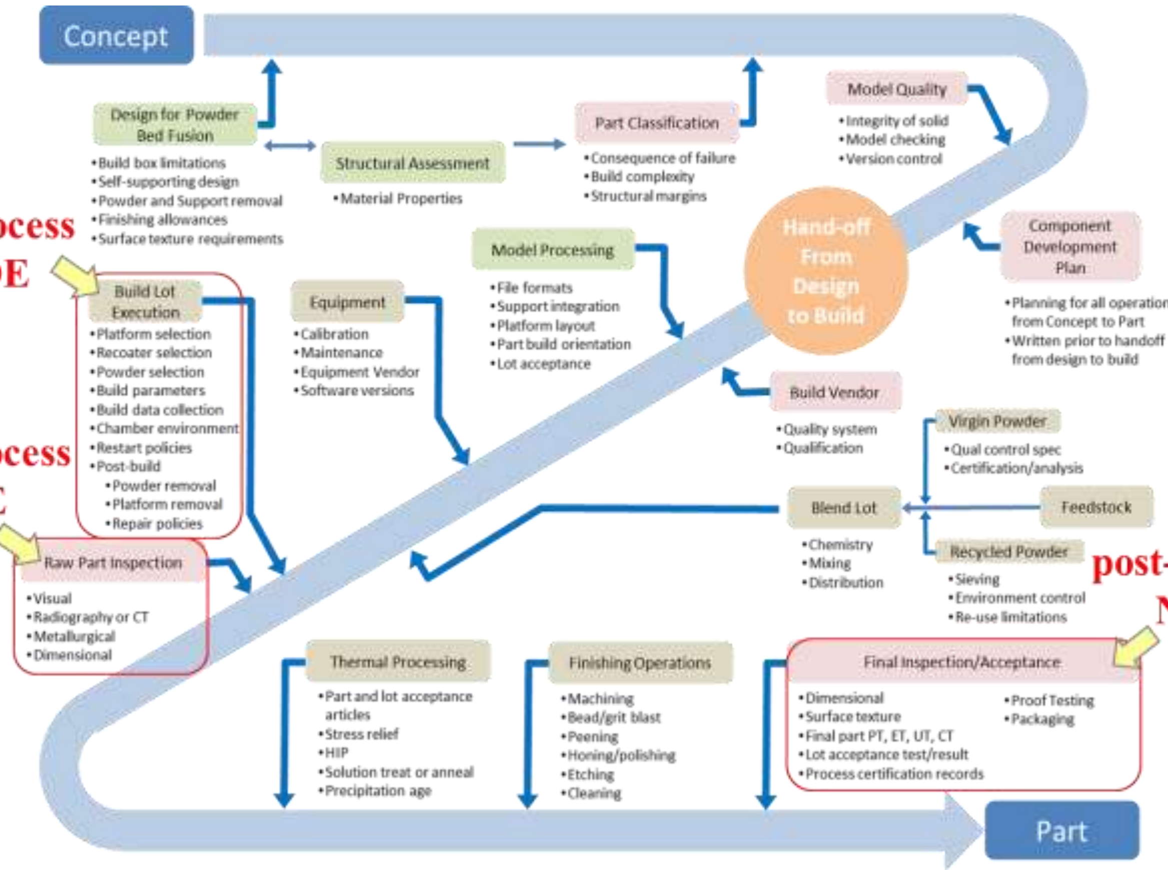
NDEure Standards for NDE of AM Aerospace Materials

Singh:
new E07
standard

→ **in-process NDE**

Waller:
WK47031

→ **post-process NDE**

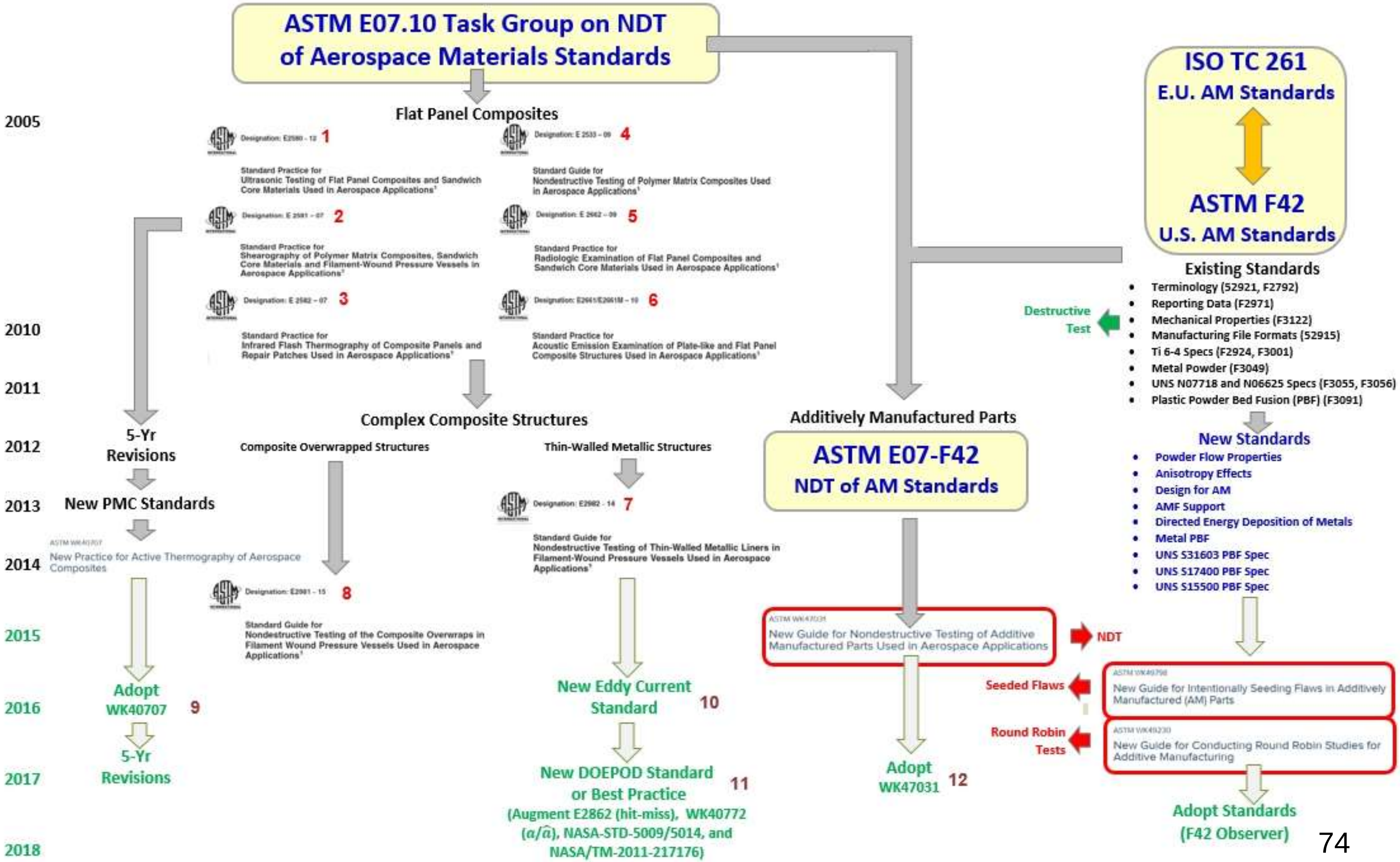


post-process NDT ←

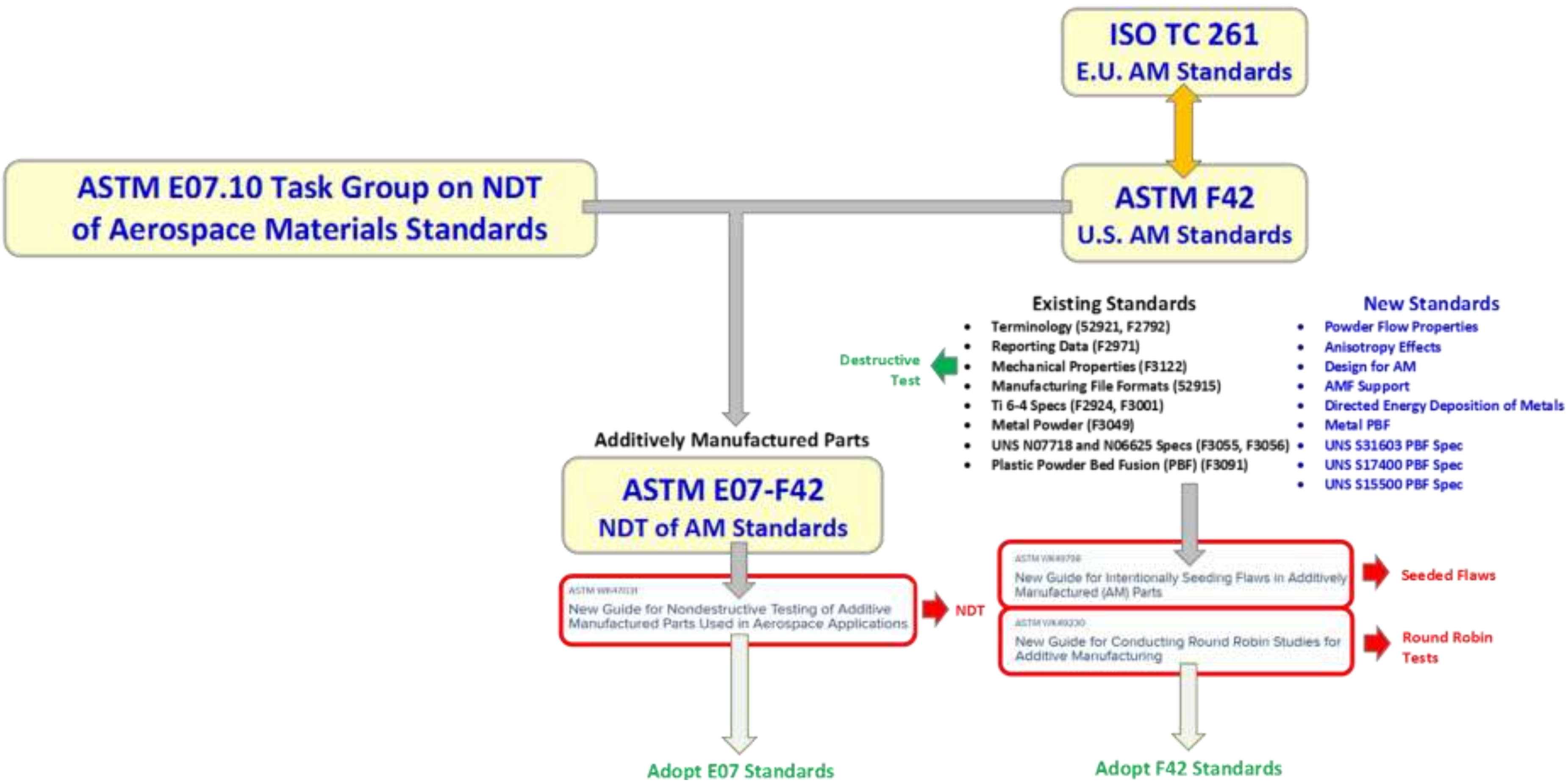
Waller:
WK47031

- *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)**

E07.10 Taskgroup on NDT of Aerospace Materials



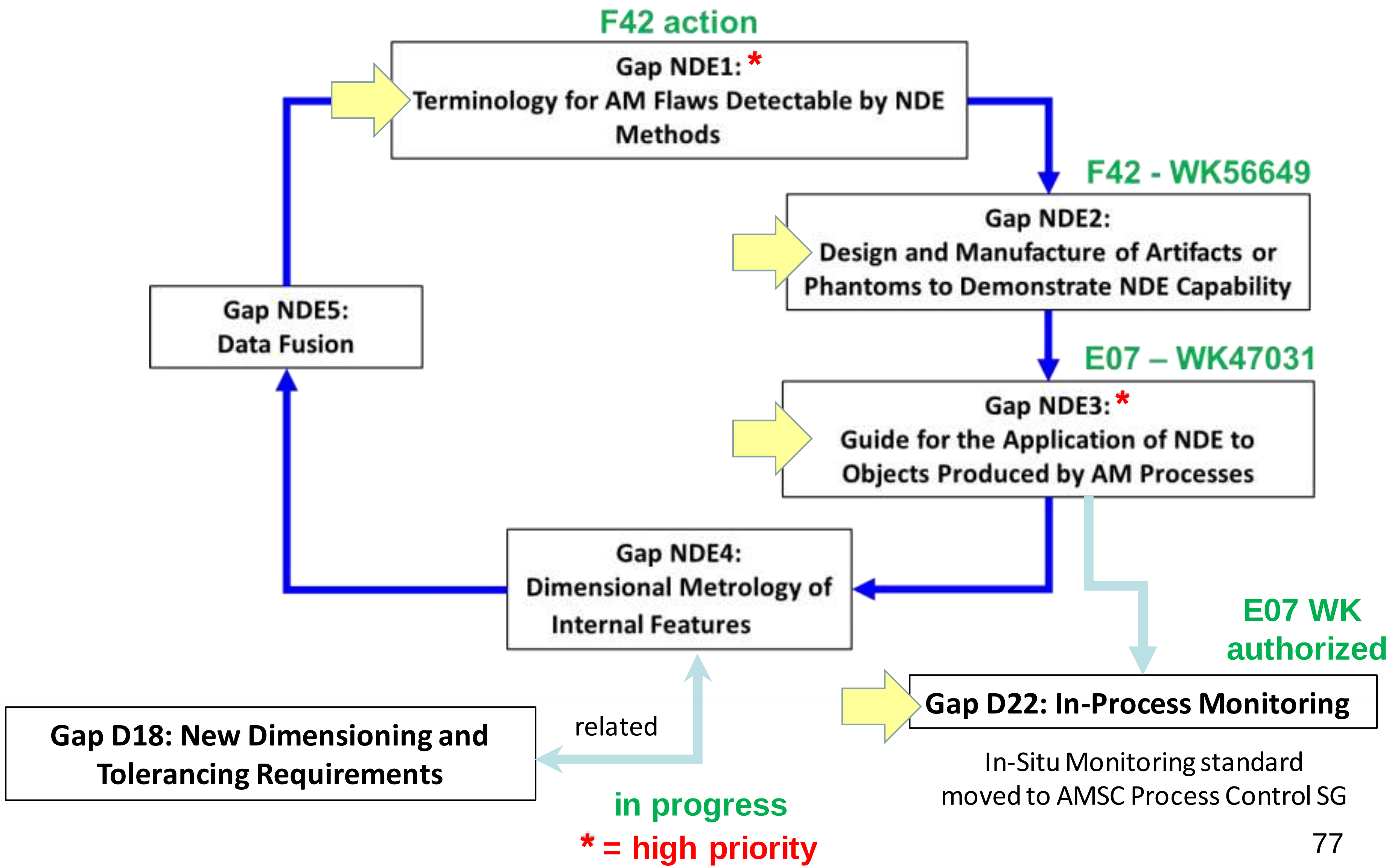
NDE of Additively Manufactured Aerospace Parts



ASTM F42/ISO TC 261 Joint Jurisdiction

JG51: Terminology
JG52: Standard Test Artifacts
JG53: Requirements for Purchased AM Parts
JG54: Design Guidelines
JG55: Standard Specification for Extrusion Based Additive Manufacturing of Plastic Materials
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
JG62: Guide for Conducting Round Robin Studies for Additive Manufacturing
JG63: Test Methods for Characterization of Powder Flow Properties for AM Applications
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



AMSC Gap NDE1: Proposed Terminology for AM Defects

Proposed Terminology:

ASTM F42
ISO/ASTM 52900 Defect Terminology Harmonization

Existing Terminology in ISO/ASTM 52900:

porosity, *n*—*property*, presence of small voids in a **part** making it less than **fully dense**. (see proposed new definition below)

DISCUSSION—Porosity may be quantified as a ratio, expressed as a percentage of the volume of voids to the total volume of the part.

part, *n*—joined material forming a functional element that could constitute all or a section of an intended product.
DISCUSSION—The functional requirements for a part are typically determined by the intended application.

Existing Terminology in E1316:

defect, *n* —see Terminology E1316. (One or more flaws whose aggregate size, shape, orientation, location, or properties do not meet specified acceptance criteria and are rejectable.) Post-processing may eliminate or heal certain defects.

NOTE—NDT standard defect classes for welds and castings (welding and casting defect quality standards) will generally not be applicable for additive manufactured parts.

flaw, *n* —see Terminology E1316. (An imperfection or discontinuity whose aggregate size, shape, orientation, location, or properties) are not necessarily rejectable.) Examples include porosity/voids (isolated or cluster, surface or deeply embedded), lack of fusion, layer defects (planar or linear), cross-layer defects, start-stop errors, inclusions, layer shifts, under/over-melted material, metastable microstructures, residual stress, and poor dimensional accuracy. Post-processing may eliminate or heal certain flaws.

discontinuity, *n*—see Terminology E1316. a lack of continuity or cohesion; an intentional or unintentional interruption in the physical structure or configuration of a material or component.

Proposed Terminology in ASTM F42 WK56649:

embedded flaw, *n* — a **flaw** that is completely surrounded by the parent material.

surface-connected flaw, *n* — a **flaw** that is in the body of the material but its boundary reaches (is open) to the part's surface. Synonym: surface flaw.

Common to DED and PBF (distinguish any process differences):

balling, *n*—a flaw caused by scanning speed, low laser power, increased thickness of powder layer or high levels of oxygen.

crack, *n* —high intensity (focused) beams and fast cooling rates in PBF (and DED?) processes can lead to large thermal gradients in a part. The **residual stresses** caused by cooling can cause **delamination** of a part from the build plate, or stress cracking in the part, especially in large components. Sintering cracks may also occur due to incomplete fusion.

delamination, *n* — high intensity (focused) beams and the fast cooling rates in PBF (and DED?) processes can lead to large thermal gradient through a part. The **residual stresses** caused by cooling can cause delamination of a part from the build plate, or **cracking** in the part, especially in large components.

hole, *n* —see **void**.

inclusion, *n* — foreign material incorporated in a part due to use of contaminated or impure feedstock, or introduction of debris from the production environment during processing or post-processing. Inclusions can be metallic or nonmetallic. Metallic inclusions are typically oxides, nitrides, hydrides, carbides, or combinations thereof.

keyhole, *n* — a **flaw** caused by changes in the energy density of the impinging beam, creating deeper pockets of molten material in the melt pool and vaporization of the metal above the melt pool that entrap voids or create **spatter** (spherical molten ejecta). The resulting voids and holes may be covered by subsequent layers of fused material.

(NEW) **porosity**, *n*—*property*, presence of small **voids** in a **part** making it less than **fully dense**. Porosity is created either by a breach in the build container's atmosphere in DED, or in PBF, from trapped gas in the powder feedstock (see **gas porosity**). Porosity in as-built parts can be reduced or eliminated by heat treatment, for example, hot isostatic pressing (HIP). Large pores may not be completely healed and may be of interest for detection by NDT. Porosity flaws are generally described as being spherical, and may be embedded or surface-breaking, and isolated or interconnected. Like **voids** and **unconsolidated powder**, porosity causes a part to be less than **fully dense**.

DISCUSSION—Porosity may be quantified as a ratio, expressed as a percentage of the volume of voids to the total volume of the part.

NOTE—Scanning at reduced scan speed leads to **porosity** formation, while scanning at a high speed can lead to **unconsolidated powder/lack of fusion** discontinuities.

gas porosity, *n*—a type of **porosity** formed during processing or post-processing that remains 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.

stop/start flaws, *n*—a type of **flaw** that is the consequence of long builds or interruption of feedstock (short feed during the re-coating of consecutive build layers) which can lead to a reduction of mechanical properties in its vicinity due to incomplete fusion, inherent material weakness, or layer misalignment.

surface roughness, *n*—Poor surface finish, more prominent in laser versus electron beam **powder bed fusion**.

surface flaws, *n*—discontinuities or imperfections on a part surface. Examples include partially fused powder, and linear or planar irregularities. Surface flaws have features similar to spatter, undercut, irregular top bead, ropey bead, and slumping noted in welded parts.

void, *n* —**flaws** created during the build process that are empty pockets or filled with partially or wholly un-sintered powder, or partially or wholly un-fused wire. These pockets can exist in a variety of shapes and sizes. Voids are distinct from porosity, and are the result of lack of fusion or 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 porosity, voids cause a part to be less than **fully dense**.

reduced dimensional accuracy, *n*—*property*, deviation of measured part dimensions (external, internal, lattice, custom) from dimensions called out by specification or drawing, caused by **residual stresses**, regions in a part with low geometrical stiffness such as thin walls and overhang structures, or regions where there are steps parallel to the build direction caused by adjacent layers.

reduced mechanical properties, *n*—*property*, a property caused by rapid cooling or excessive thermal gradients resulting in warpage or reduced mechanical properties.

NOTE—**residual** stresses produced by rapid cooling from the melt can place certain regions of a part (surfaces or areas with high thermal gradients) in a state of pre-stress, thus reducing the effective structural load that can be applied on the part, or causing structural weaknesses in a part in regions that have **reduced mechanical properties** compared to the rest of the part.

residual stress, *n*—*property*, a property caused by overly rapid cooling or excessive thermal gradients (poor process parameterization) resulting in warpage or reduced mechanical properties.

NOTE—**residual** stresses produced by rapid cooling from the melt can place certain regions of a part (surfaces or areas with high thermal gradients) in a state of pre-stress, thus reducing the effective structural load that can be applied on the part, or causing structural weaknesses in a part in regions that have **reduced mechanical properties** compared to the rest of the part.

Unique to PBF:

unconsolidated powder, *n* — a flaw created from a malfunction of the laser or electron beam speed or power, contamination, or other incorrectly adjusted parameters, resulting in the formation of unsintered or loosely agglomerated particles such that the part is less than **fully dense**. This type of **flaw** occurs in at least one layer, and can affect a significant amount of the total volume of a part. When this type of **flaw** extends across multiple layers, it typically occurs in an angle displaced in the scanning direction as successive build layers are fused. The volume occupied by the unconsolidated powder can have be irregularly shaped and may contain **trapped powder**. Synonym: **lack of fusion (LOF)**.

layer flaw, *n* —a type of **void** that tends to grow/propagate along the layer planes during the **powder bed fusion** process. Example: skipped layers.

cross layer flaw, *n* — a type of **void** that tends to grow/propagate along the build axis during the **powder bed fusion** process.

trapped powder, *n*—see **unconsolidated powder**.

lack of fusion (LOF), *n*—see **unconsolidated powder**

Unique to DED:

incomplete fusion, *n* — a **flaw** created from a malfunction of the laser or electron beam speed or power, contamination, or other incorrectly adjusted parameters, resulting in the formation of unfused, undermelted material such that the part is less than **fully dense**. Analogous to **unconsolidated powder** in powder bed fusion.

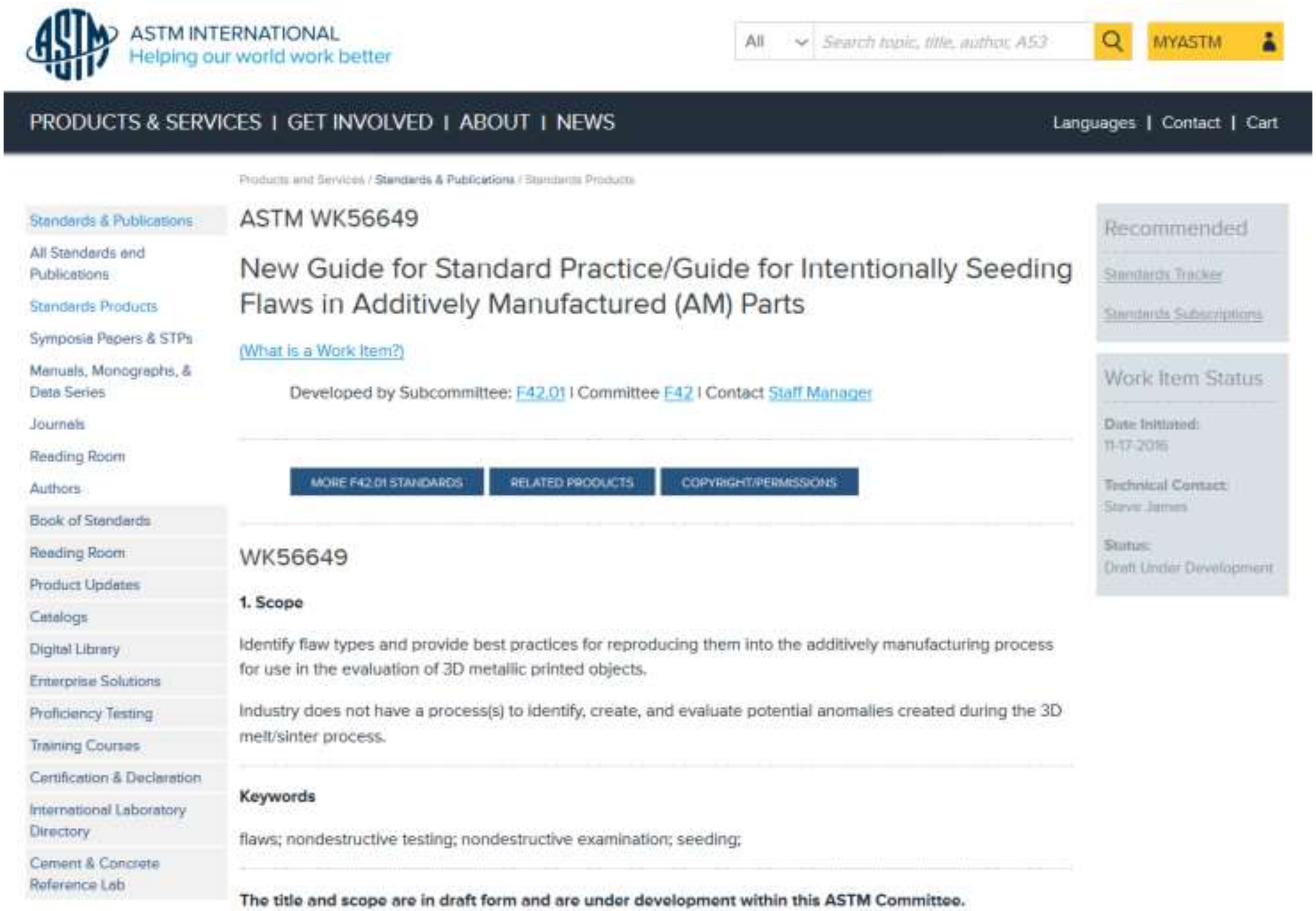
non-uniform weld bead and fusion, *n*—

undercuts, *n*—

- 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)

AMSC Gap NDE2: ASTM F42 Work Item WK56649

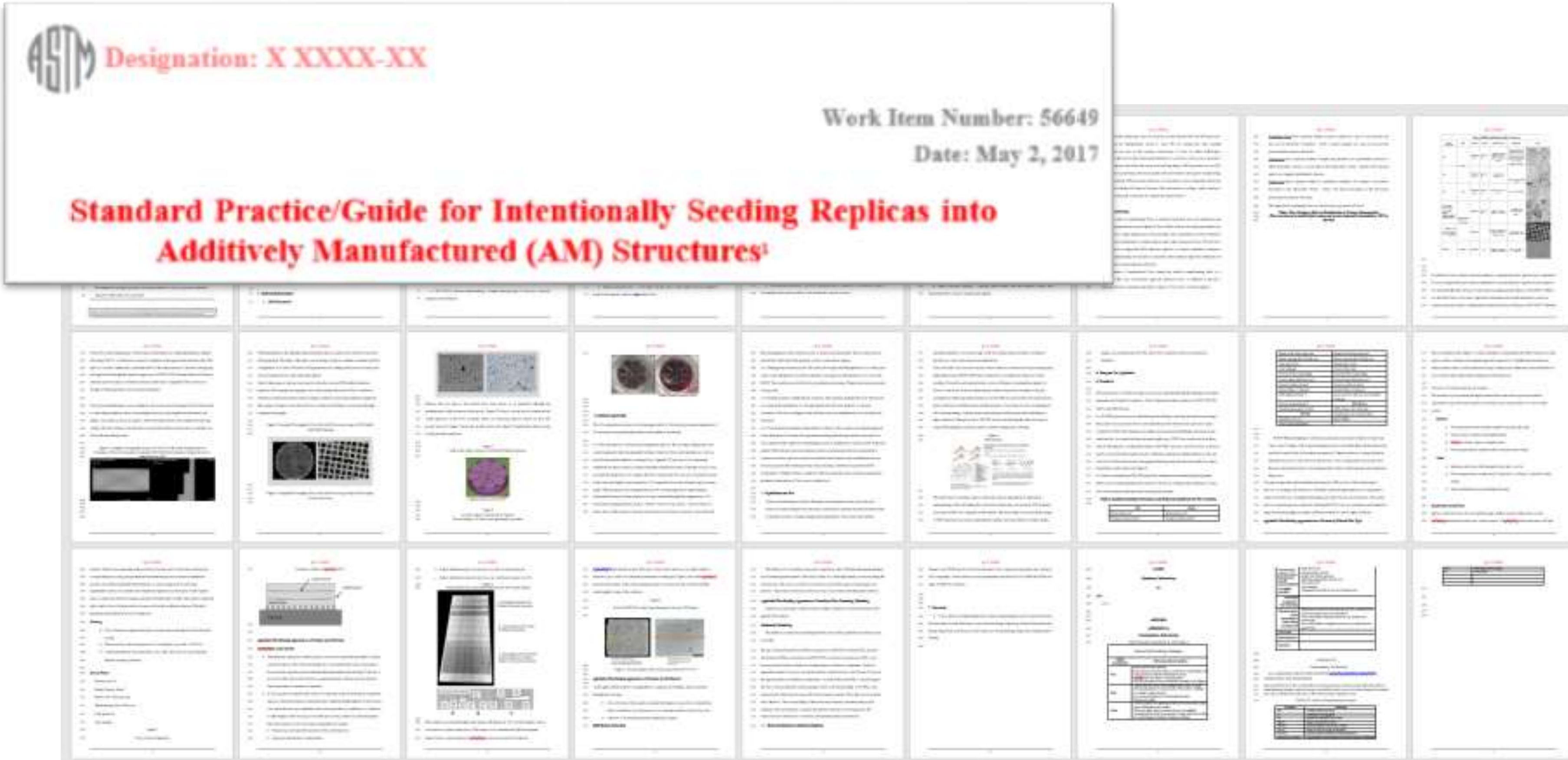
- ASTM F42 Work Item WK56649: *Standard Guide for Intentionally Seeding Flaws in Additively Manufactured (AM) Parts* (Technical Contact: **Steve James**)



https://www.astm.org/WorkItems/WK56649.htm

AMSC Gap NDE2: ASTM F42 Work Item WK56649: Seeded Flaws

- ASTM F42 Work Item WK56649 (Technical Contact: **Steve James**)


Designation: X XXXX-XX

Work Item Number: 56649

Date: May 2, 2017

Standard Practice/Guide for Intentionally Seeding Replicas into Additively Manufactured (AM) Structures[1]

- 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

AMSC Gap NDE3: ASTM E07 Work Item WK47031

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- Cement & Concrete Reference Lab

ASTM WK47031

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

(What is a Work Item?)

Developed by Subcommittee: E07.10 | Committee E07 | Contact Staff Manager

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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

Recommended

- Standards Tracker
- Standards Subscriptions

Work Item Status

Date Initiated: 08-14-2014

Technical Contact: Jess Waller

Item: 001

Ballot: E07.10 (17-03)

Status: Negative Votes Need Resolution

https://www.astm.org/WorkItems/WK47031.htm

79 current members

Collaboration Area

Collaboration on WK47031

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

Created: Target Date: 2018-10-01 Technical Contact : Jess Waller

Drafts | File Repository | Members | History

Task Group Members

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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)

AMSC Gap NDE3: balloting status

Designation: X XXXX-XX

Work Item Number: 47031
Date: July 12, 2017

Standard Guide for Nondestructive Testing of Metal Additively Manufactured Aerospace Parts After Build[1]

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

- 1 negative/4 comments from May balloting resolved/incorporated
- ECT section added
- Re-balloted 7/14/27, closing date 8/14/17

AMSC Gap NDE3: Similar U.S./E.U. Efforts

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

Draft WK47031

ASTM E07.10 NDT of AM Guide

Approved NP52905

ISO TC 261 JG59 Best NDE Practice

- 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

AMSC Gap NDE3: Features/Scope

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[1]

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 (□) 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.

AMSC Gap NDE3: Features/Scope

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 as1) 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.

AMSC Gap NDE3: Features/Address Process Considerations

Type	Technologies
Powder Bed Fusion (powder)	Electron Beam Melting (EBM)
	Selective Laser Melting (SLM)
	Selective Laser Sintering (SLS)
	Direct Metal Laser Sintering (DMLS)
Directed Energy Deposition (powder or wire)	Electron Beam Freeform Fabrication (EBF^3)
	Laser Beam (LB)
	Gas Tungsten Arc (GTA), Plasma Arc PA), Plasma Transferred Arc (PTA), and Gas Metal Arc (GMA)

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.

AMSC Gap NDE3: Features/Address Defect Classes

TABLE 4.2 Additive Manufacturing Defect Classes and Subclasses [A]

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

[A] Abbreviations used: ... = not applicable, DED = Directed Energy Deposition, HAZ = Heat Affected Zone, HIP = Hot Isostatic Pressing

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

AMSC Gap NDE3: Features/Address Process-Defect-NDE Relationships

TABLE 4.1 Nondestructive Test Detection of Typical Additive Manufacturing Flaws [A, B]

Flaw/Artifact[C]	Observed in PBF or DED?	Why?	Post-Process Detection	Comment
Porosity	both	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.	Depending on sample geometry and size of porosity may be detected using CT/ECT[G]/PCRT/RT/UT	HIP recoverable (may not be full)
Voids	both	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.	Depending on sample geometry and size of voids may be detected using CT/ ECT[G]/PCRT/RT/UT	HIP recoverable depending on size (not be fully recoverable regardless)
Layer defects	Unique to AM[F]	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.	Depending on sample geometry and size of flaw may be detected using CT/ECT[G]/PCRT/RT/UT	HIP recoverable depending on size (not be fully recoverable regardless)
Cross-layer defects	Unique to AM[F]	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.	Depending on sample geometry and size of flaw may be detected using CT/ECT[G]/PCRT/RT/UT	HIP recoverable depending on size (not be fully recoverable regardless)
Under melted material/unconsolidated powder (LOF)	both	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.	Most probably CT, and PCRT, detectability depends on sample geometry and size PCRT	Only fixable during the process
Cracking[D]	Unique to AM[F]	AM PBF failure to completely clean one alloy powder from the build environment prior to processing another, DED	Depending on sample geometry and size of crack may be	···

- Links defect with probable process cause and recoverability by post-processing, and applicable NDE methods.

AMSC Gap NDE3: Features/ Address Process-Defect-NDE Relationships

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**	**ECT**	**MET[B]**	**PCRT**	**PT**	**TT**	**UT**	**AE**	**LT**	**ND**	**MT**	**VT**
Surface	X[C]	X[D]	X	...	X[D]	...	...	...	...	...	...	X
Porosity	X	X[D]	...	X	X[D]	...	X	...	...	...	...	X[E]
Cracking	X	X[D]	...	X	X[D]	X	X	X	X[F]	...	X	X
Lack of Fusion	X	X[D]	...	X	X[D]	X	X	X	...	...	X	...
Part Dimensions	X	...	X	...	...	...	...	...	...	...	...	...
Density[G]	X[H]	...	...	...	...	...	...	...	...	...	...	...
Inclusions	X[I]	X[D]	...	...	...	X	X	...	...	...	...	...
Discoloration	...	...	...	...	...	...	...	...	...	...	...	X
Residual Stress	...	X[D,J]	...	...	...	...	...	...	...	X	...	...
Hermetic Sealing	...	...	...	...	...	...	...	...	X[F]	...	...	...

[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] 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).

[D] Applicable if on surface.

[E] Macroscopic cracks only.

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

[G] Pycnometry (Archimedes principle).

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

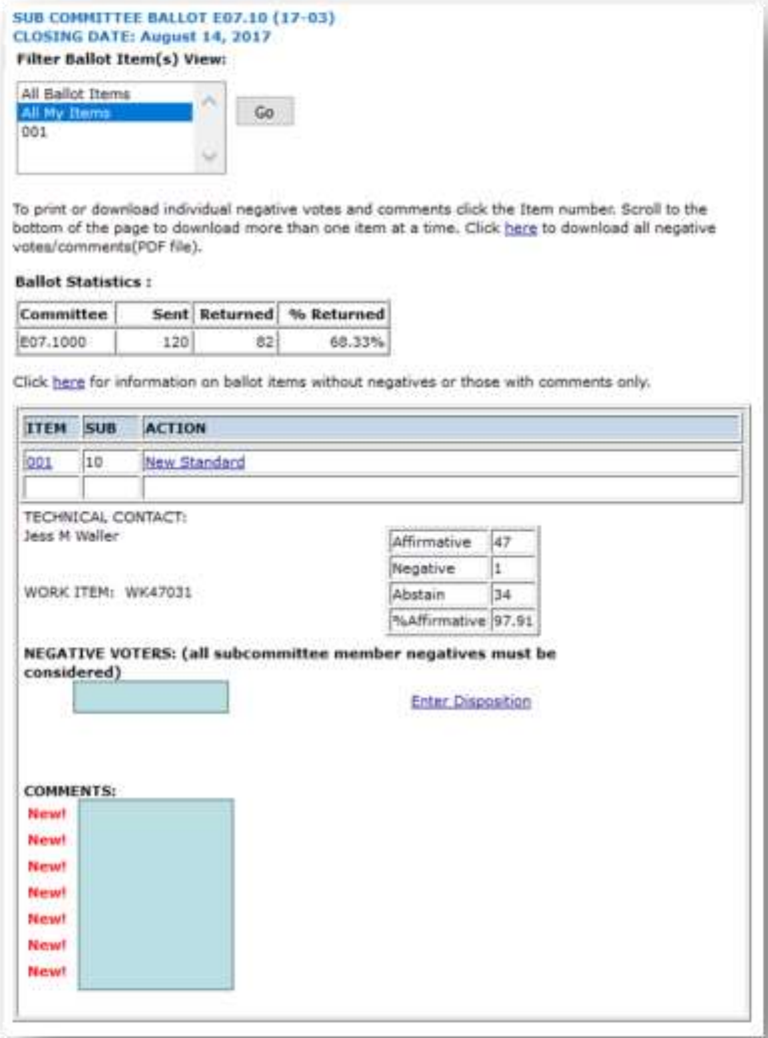
[I] If inclusions are large enough and sufficient scattering contrast exists.

[J] Residual stress can be assessed if resulting from surface post-processing (for example, peening).

- Links defect class with applicable NDE methods covered and not covered by the Guide.

AMSC Gap NDE3: Balloting Status

- 17-03 E07.10 subcommittee ballot results closing 8/14/17
  - 1 Negative
  - 7 Comments


SUB COMMITTEE BALLOT E07.10 (17-03)
CLOSING DATE: August 14, 2017

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Ballot Statistics :

Committee	Sent	Returned	% Returned
E07.1000	120	82	68.33%

Click here for information on ballot items without negatives or those with comments only.

ITEM	SUB	ACTION
001	10	New Standard

TECHNICAL CONTACT:
Jess M Waller

WORK ITEM: WK47031

Affirmative	47
Negative	1
Abstain	34
%Affirmative	97.91

NEGATIVE VOTERS: (all subcommittee member negatives must be considered)

Enter Disposition

COMMENTS:
New!
New!
New!
New!
New!
New!
New!

- Next balloting cycle planned for February-March.

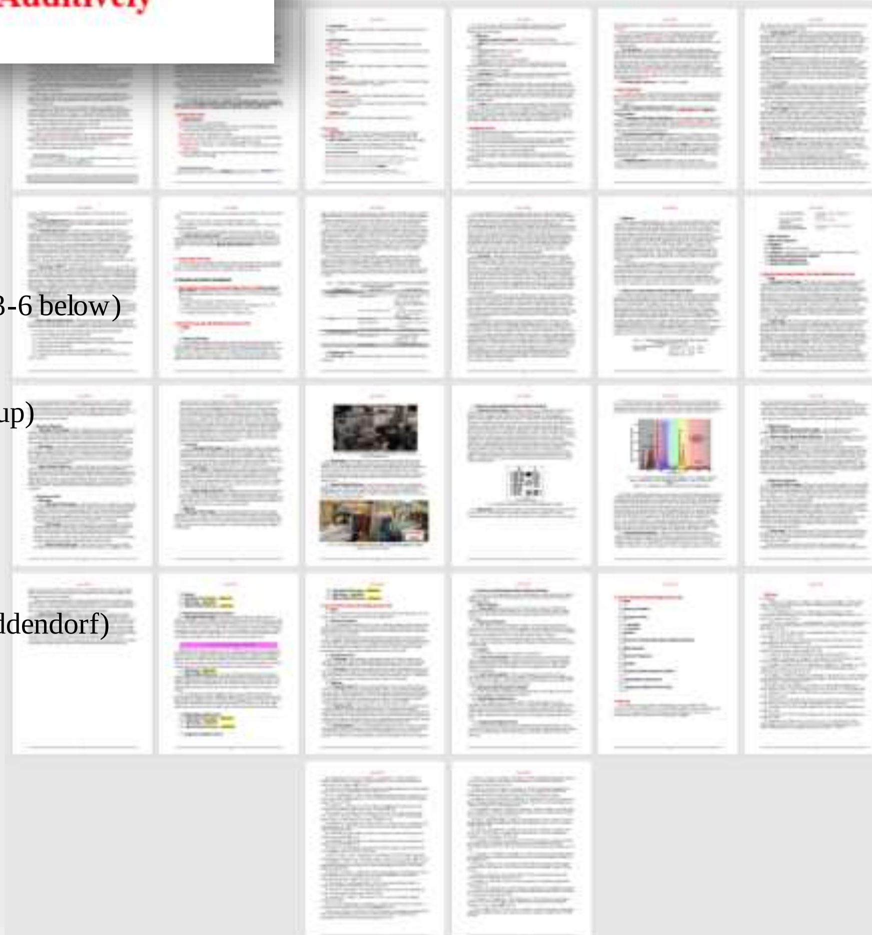
AMSC Gap D22: In-Process Monitoring (Proposed E07 Standard)

Designation: X XXXX-XX

Work Item Number: TBD

Date: December 2017

Standard Guide for In-Process Monitoring of Metal Additively Manufactured Aerospace Parts During Build[1]



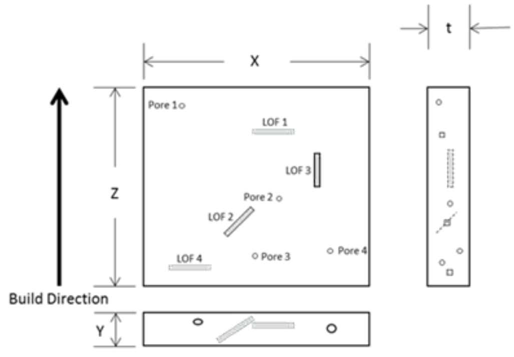
- Telecon held 12/19/17
- Draft available
- Writing teams established
  1) Sensor selection (address sensors for different techniques 3-6 below)
     a. Surendra Singh (lead)
     b. Prabir Chaudhury/Exova
  2) Draft new content for IR melt pool monitoring (NIST, group)
     a. Brandon Lane (lead)/NIST
     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

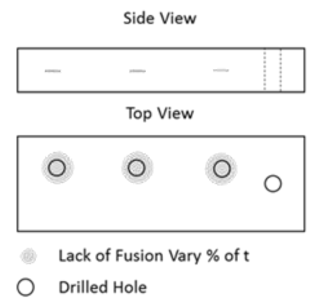


Artifact Lack of Fusion	Depth	Length	Orientation to build direction
LOF 1	1% of Thickness or 1 layer x ¼ t	.25" (6.35mm)	0°
LOF 2	2% of Thickness or 2 layers x ¼ t	.25" (6.35mm)	45°
LOF 3	3% of Thickness or 3 layers x ¼ t	.25" (6.35mm)	90°
LOF 4	4% of Thickness or 4 layers x ¼ t	.25" (6.35mm)	0°

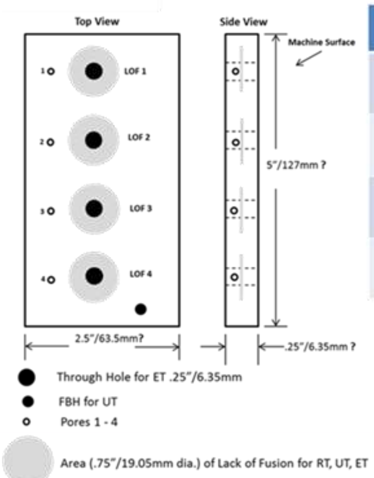
Artifact	Diameter
Pore 1	.5% of t
Pore 2	1% of t
Pore 3	1.5% of t
Pore 4	2% of t

Reference: ASTM E 1320 *"Standard Reference Radiographs for Titanium Castings"*

ECT Sample



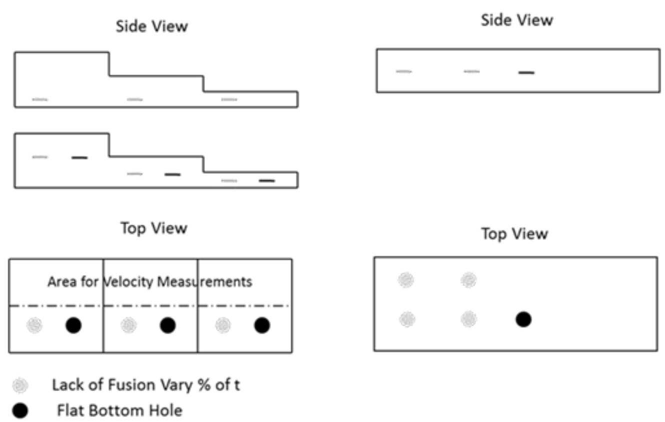
Multiuse Sample (MUS)



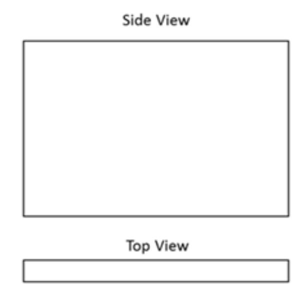
Artifact Lack of Fusion	Depth	Diameter	Orientation to build direction
LOF 1	1% of Thickness or 1 layer x 1/4t	TBD	0°
LOF 2	2% of Thickness or 2 layers x 1/4t	TBD	0°
LOF 3	3% of Thickness or 3 layers x 1/4t	TBD	0°
LOF 4	4% of Thickness or layers x ¼ t	TBD	0°

Artifact	Diameter
Pore 1	.5% of t
Pore 2	1% of t
Pore 3	1.5% of t
Pore 4	2% of t

UT Sample
Stepped vs. One Thickness

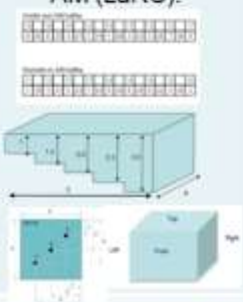
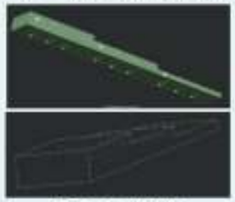


PT Sample
Fatigue Crack or Surface Texture

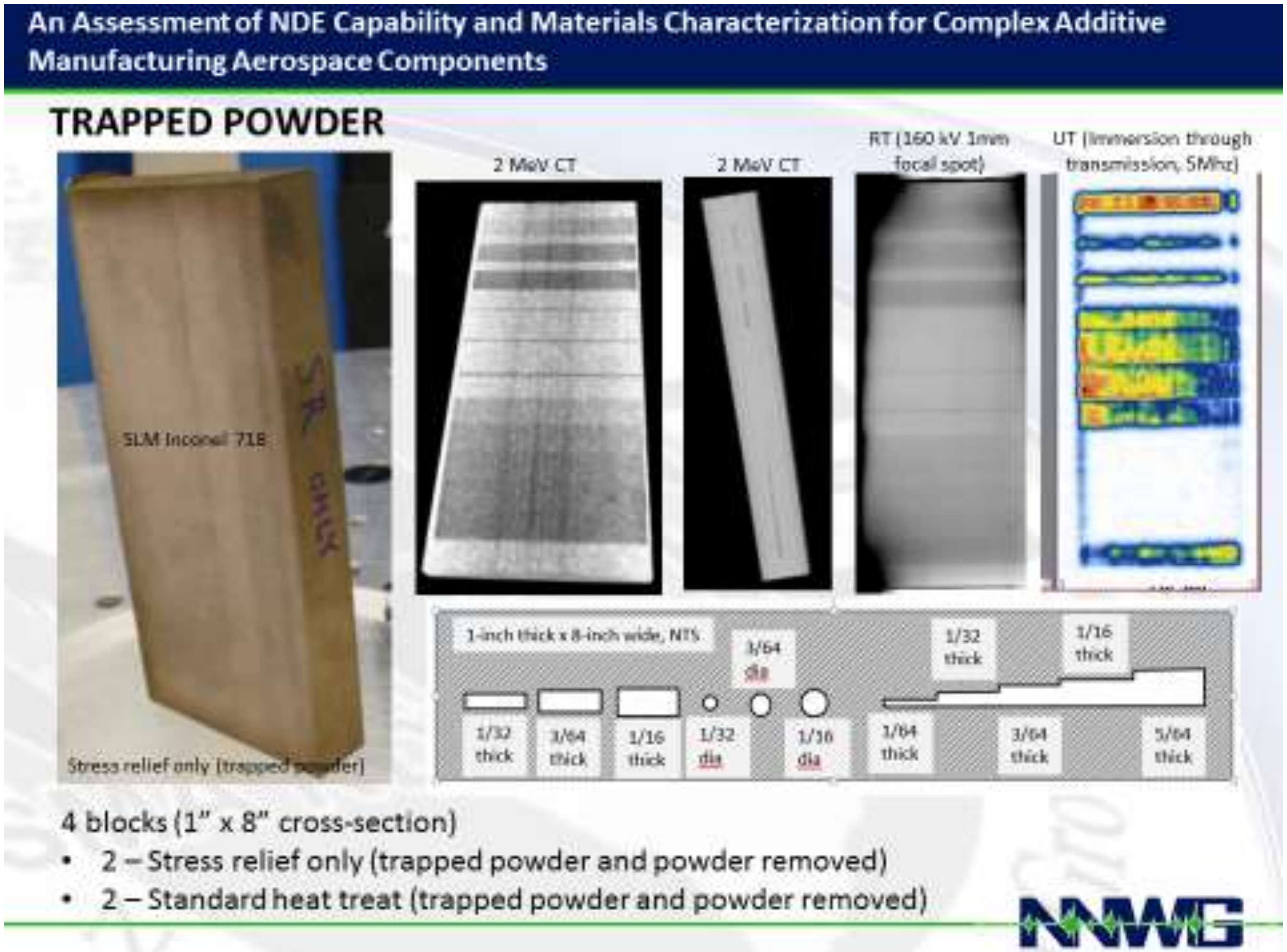


An AM panel has an EDM notched placed on one side, which is cycled to grow a through-crack for evaluation on the side opposite the notch, allowing evaluation of a tight crack on an as-built surface or the development/technical review of penetrant removal (high background issue).

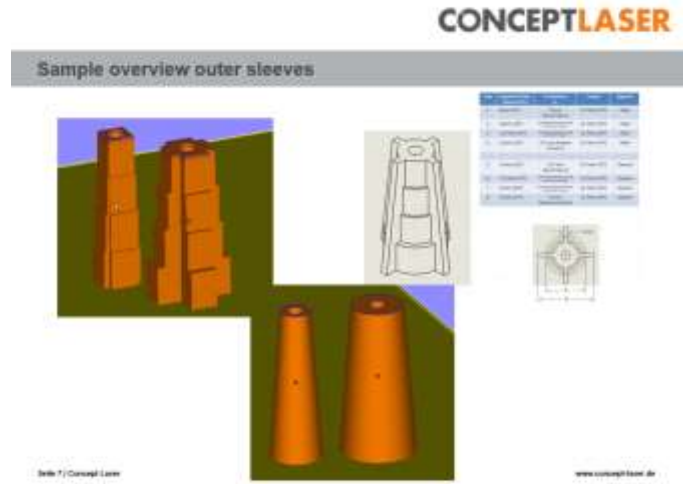
Demonstrate NDE capability

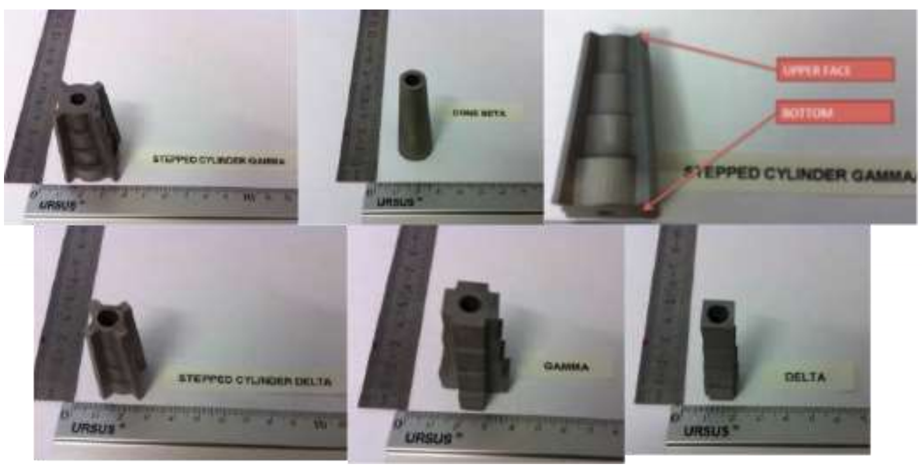
	MSFC-GRC	GSFC	LaRC	JSC-LaRC	KSC
AM process method	DMLS	DMLS (metal), LS (plastic)	LS	EBF^3	EBM
alloys	titanium, Inconel, and aluminum	titanium, SS PH1, vero-white RGD835	SS	titanium	titanium
reference standard geometries			Conventional:  AM (planned): 	wrought (JSC) and AM (LaRC): 	2nd iteration (AM):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

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

<u>CT Round Robin Testing (Previously Evaluated)</u>

Europe; The Fraunhofer Development Center X-ray Technology, Yxlon, GE
Japan; JAXA

<u>Planned Evaluation (12)</u>
N America; NASA MSFC, LMCO, Pratt & Whitnet/UTC, NASA GSFC, Boeing (two locations), GE Aviation, JHUAPL, Yxlon, UTAS, EWI, Vibrant EWI

<u>Preplanning – Participation Rules</u>

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

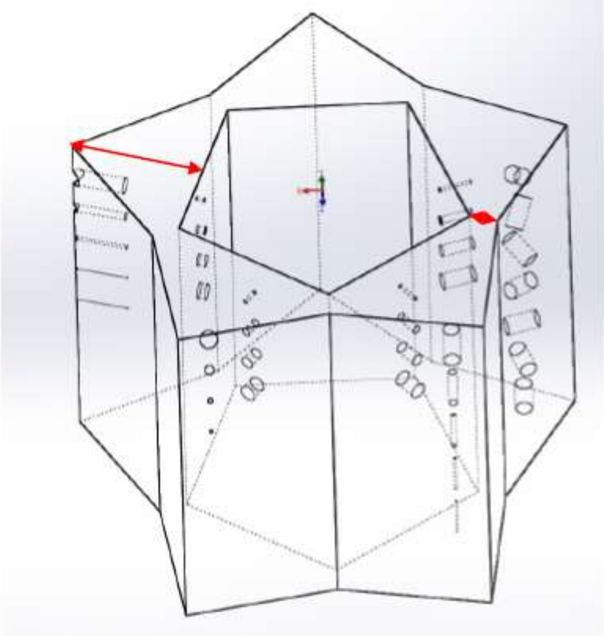
Proposed Schedule

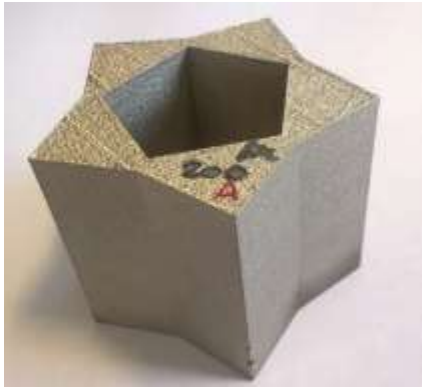
Affiliation	Date
JHUAPL	7/31 – 8/11
NASA	8/16 – 8/30
UTAS	9/4 – 9/15
PW	9/20 – 10/4
EWI	10/9 – 10/20
Boeing	10/25 – 11/8
NASA	11/13 – 12/1
AF	12/6 – 12/20
NSI	1/3 – 1/17

List with addresses will accompany the samples

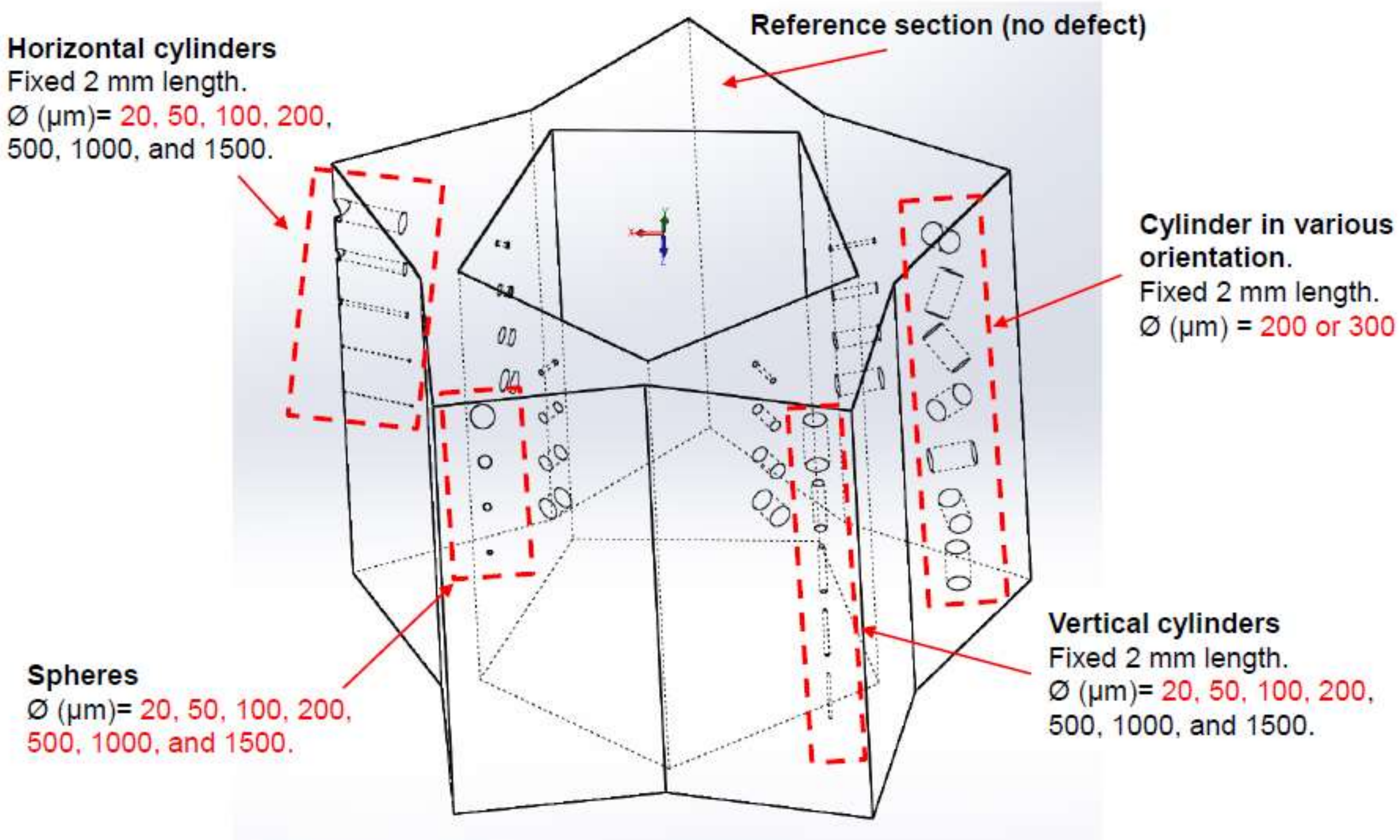
1. Star artefacts:

- <u>**Star designs are available for**</u>
  - <u>**Inconel**</u>
  - <u>**Ti**</u>
  - <u>**Al**</u>
- 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





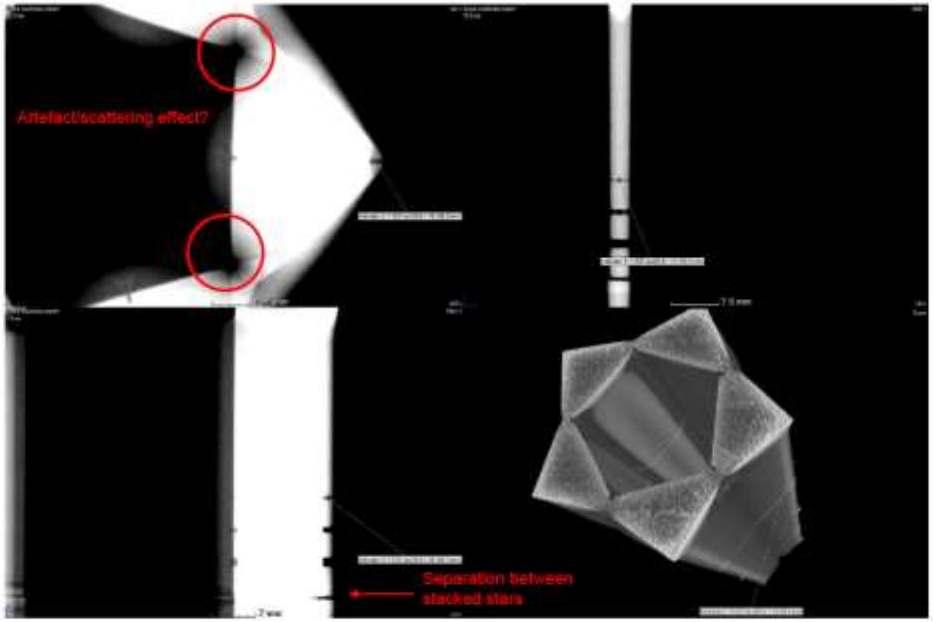
- Star artefact design: embedded feature details:



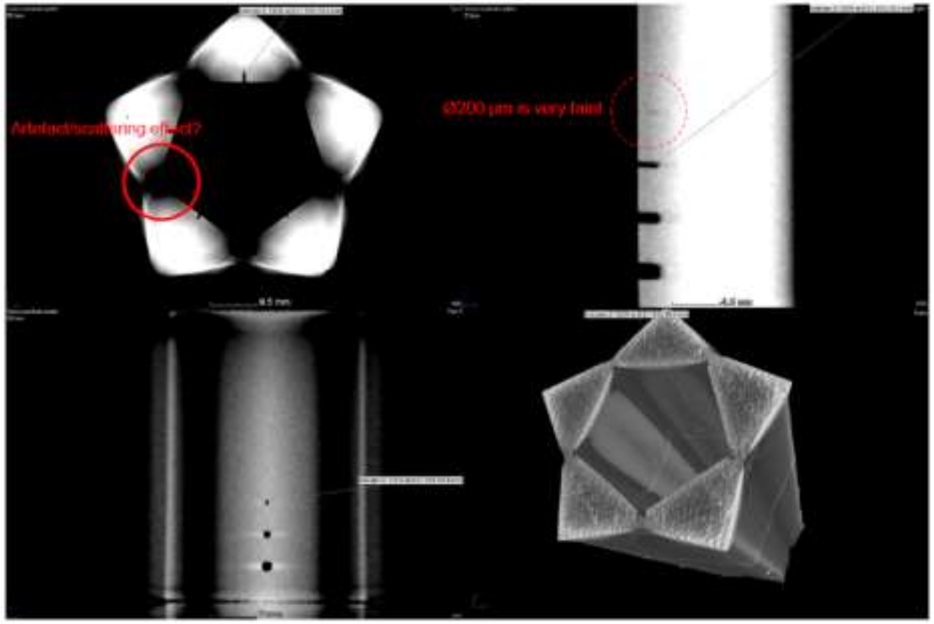
These are intentional idealized features to mimic defects (are not natural defects)

In-house CT for Inconel star artefact - horizontal cylinders (simulate layer defects):

external horizontal cylinders



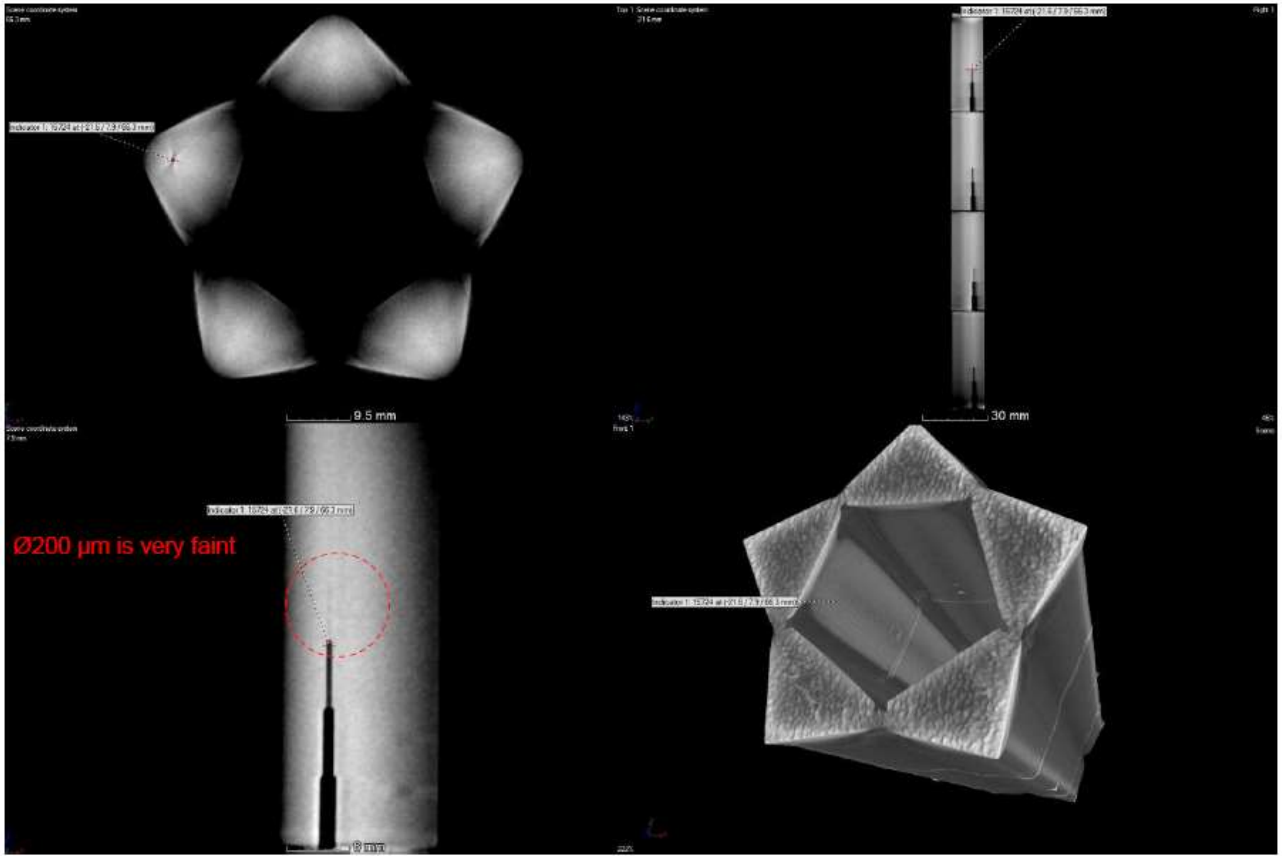
internal horizontal cylinders



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:

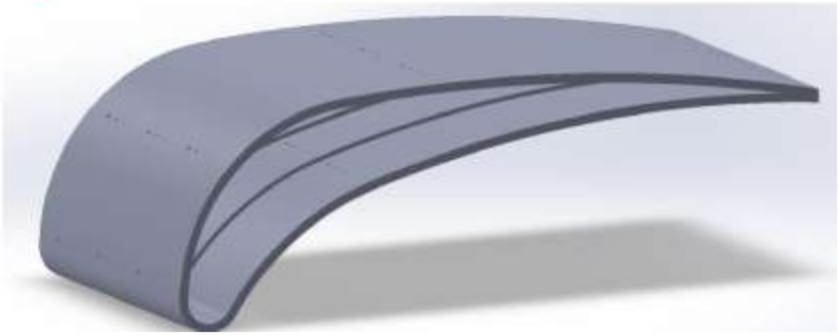
- Only the largest 3 are clearly visible (Ø500, Ø1000, and Ø1500 µm)
- Ø200 µm is very faint
- Anything smaller than Ø200 mm is not visible (Ø20, Ø50, and Ø100 µm)

ASTM WK47031 Effort: MTC Capability Demonstration Standards

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 is some locations
- Volunteers sought for Star and air foil artefact NDE

Apply NDE to understand effect-of-defect

NASA/TM-2014-218560 NDE of AM Technology Gap Analysis

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

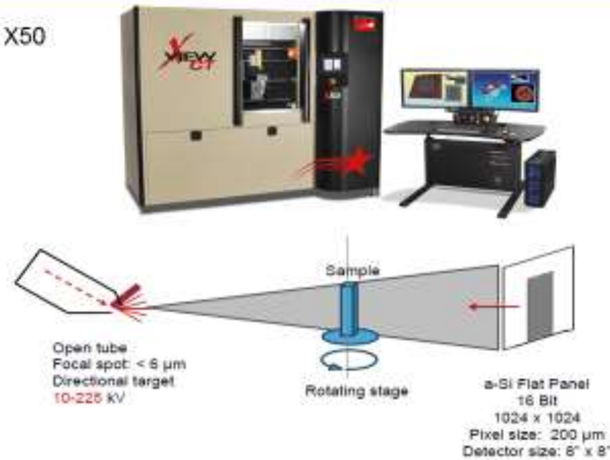
* delivered or committed to deliver samples

† E8 compliant or tensile sacrificial dogbone samples

μ–CT/CT:

CT System

NorthStar X50



Distribution A: Approved for public release; distribution unlimited. Case Number 88ABW-2016-0494

AFRL 2

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 capability at GE, Yxlon, JHU APL, JAXA, NASA MSFC, and NASA GSFC

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

Standards and Approvals for PCRT

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

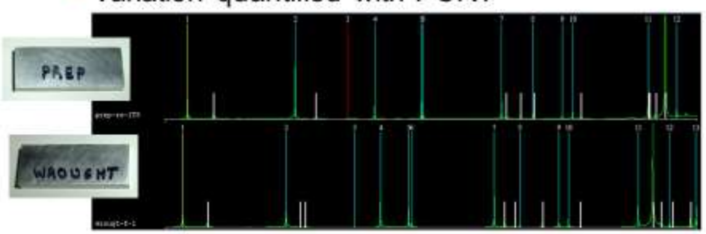
ASTM Standard Practice E2534-10 – Describes auditable method for successful application PCRT specifically and in-depth.

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

Titanium Samples

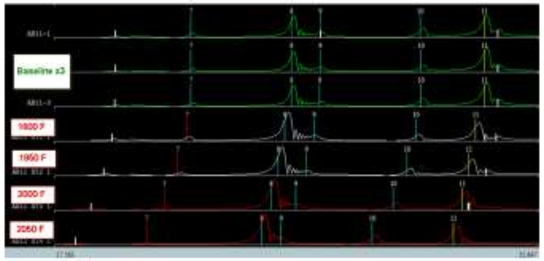
- Additive manufacturing vs. wrought
  - Same part, material variation between processes
  - Variation quantified with PCRT



12

AM Process Variation

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

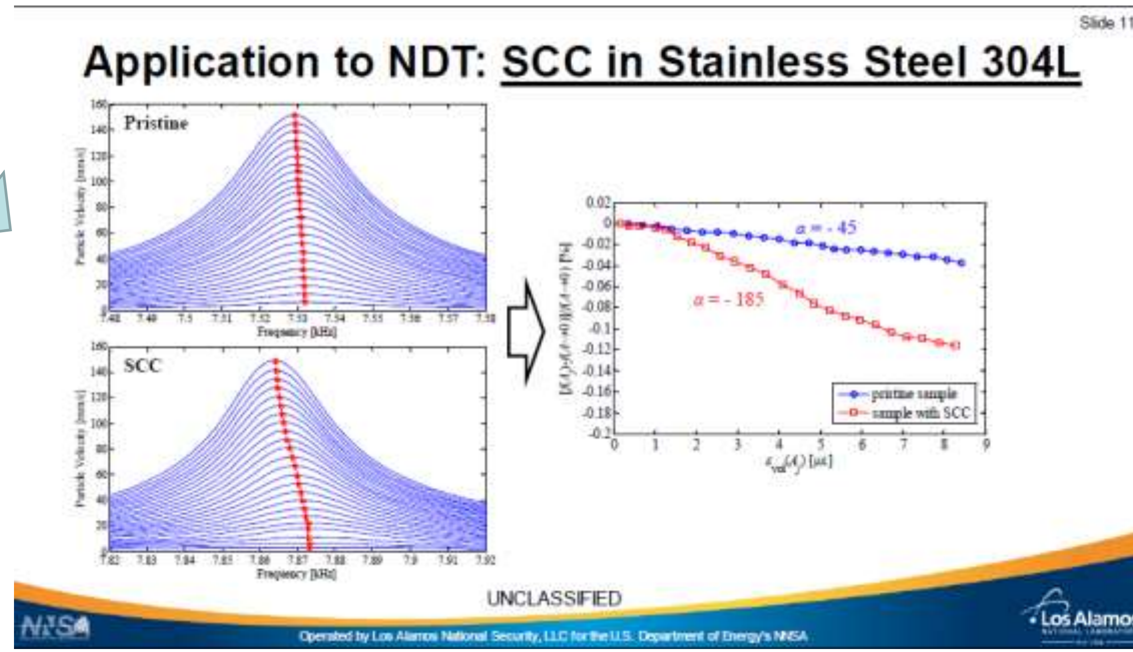


11

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

Nonlinear Resonant Ultrasonic Testing (NRUS)

TRL4 system available with advanced software



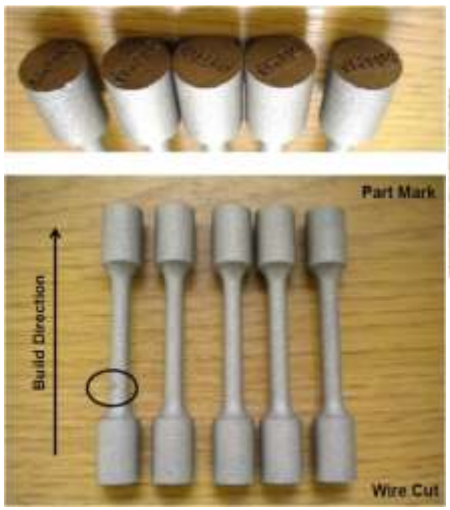
- Frequency scan at more than more amplitude
- Shows promise for detection of initial defects before catastrophic failure
- Signal not affected by part size or geometry
- MSFC to supply samples to LANL

Sacrificial Effect-of-Defect Samples

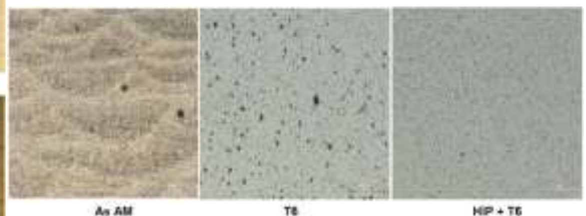
Approach

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

1. Airbus Laser PBF samples



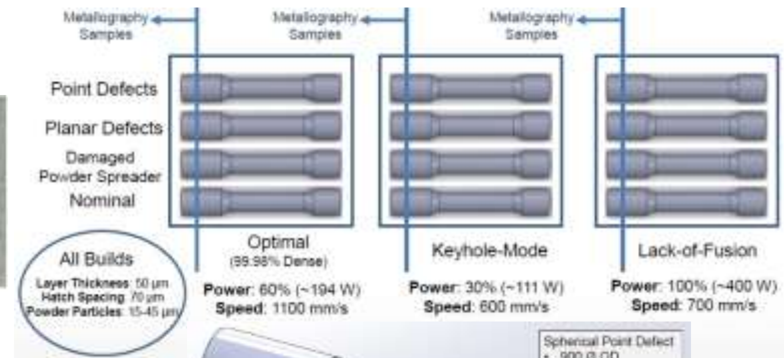
AlSi10Mg ASTM E8 compliant dogbones
13mmØ, 85mm long (6mmØ, 30mm Gauge Length)

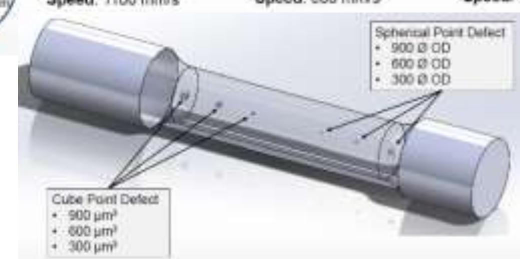


Investigate effect post-processing on microstructure and surface finish on fatigue properties

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

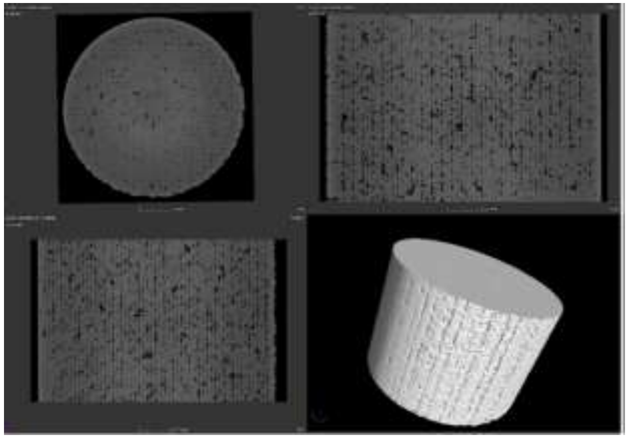
Parallel effort

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

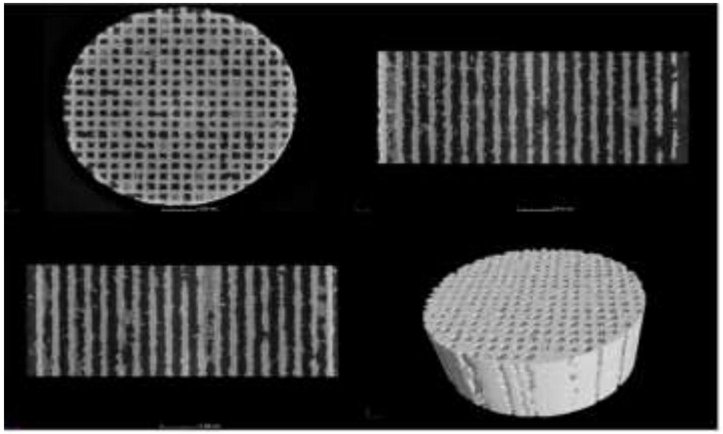
America Makes Ed Morris (VP) call to fabricate samples for NDE in support of ASTM WK47031 effort

3. CalRAM Electron Beam PBF samples

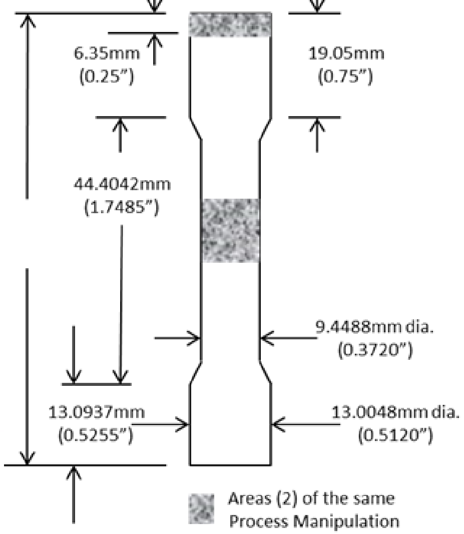
Insert 1 “Lower Laser Power”



Insert 4 “Trace Width Bigger”



ASTM E8 Complaint With off nominal locations



ASTM WK47031 Round Robin Testing (Leveraged)

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

Laser-PBF (L-PBF)

Incodema3D
Al-Si-10Mg cylinders

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

Electron Beam-PBF (E-PBF)

CalRAM
Ti-6Al-4V dogbones

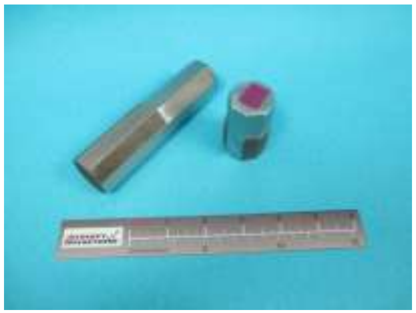
Characterized to date by various NDE methods (CT, DIC, PT, PCRT, RT, UT)

ASTM WK47031 Round Robin Testing (Leveraged)

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

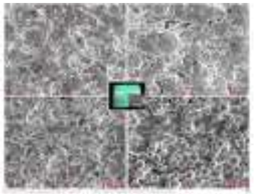
HEX Samples

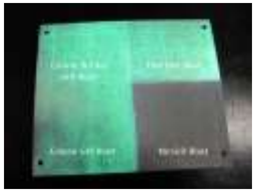
Inconel 718
in two different build orientations



SLM (L-PBF)

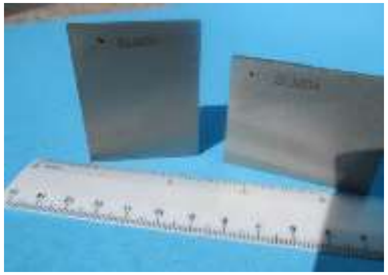
Inconel 625 PT sheets





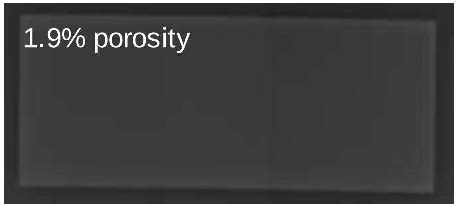
Electron Beam-PBF (E-PBF)

Met-L-Check
SS 316 PT/RT panels
w/ EDM notches



DRDC Porosity Standards

414 steel. 0-10% porosity



Directed Energy Deposition (DED)

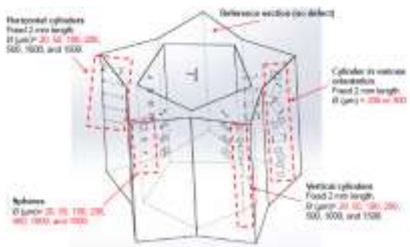
NASA MSFC ABS plastic parts with optimal and off-optimal settings (T. Prater)

ASTM/ISO Round Robin Testing

Coordinated by B. Dutton (MTC)

Star artefacts (L-PBF)

Inconel, Ti-6Al-4V



Air foil (L-PBF)

Inconel

Star artefact (E-PBF)

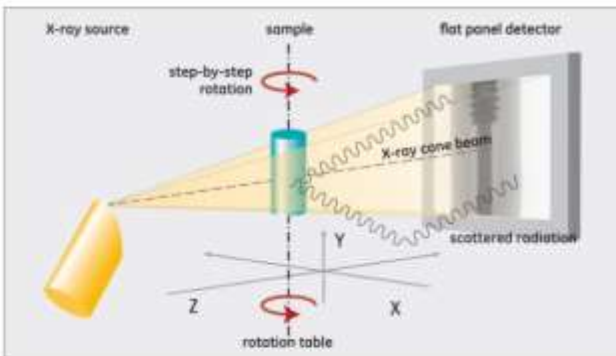
Ti-6Al-4V

Aluminum planned

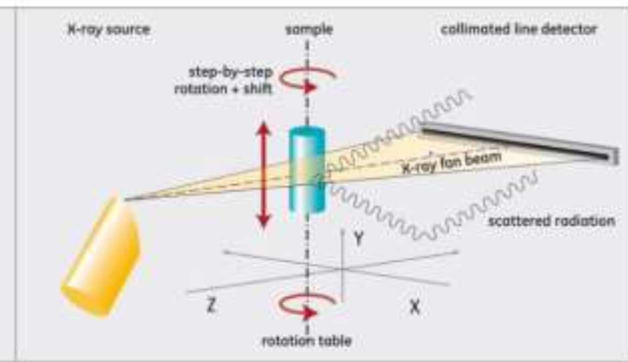
ASTM Round Robin Testing Illustrative Results

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)

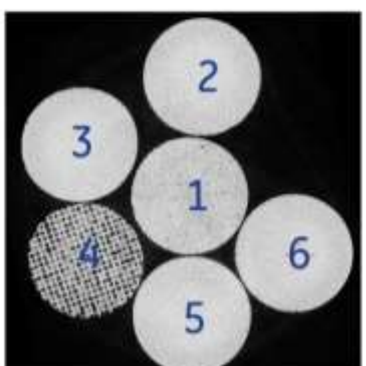


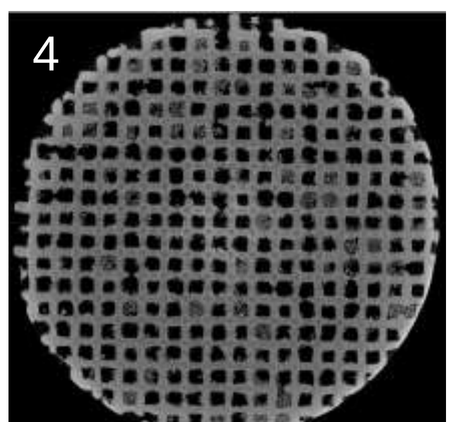
Cone beam CT (3D) is fast but scattered radiation can affect the image quality

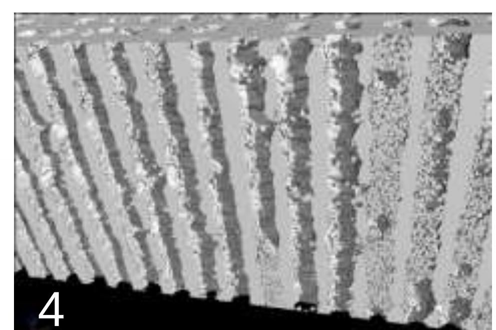


Fan beam CT is not affected by scattered radiation but is slow

Concept Laser CT inserts

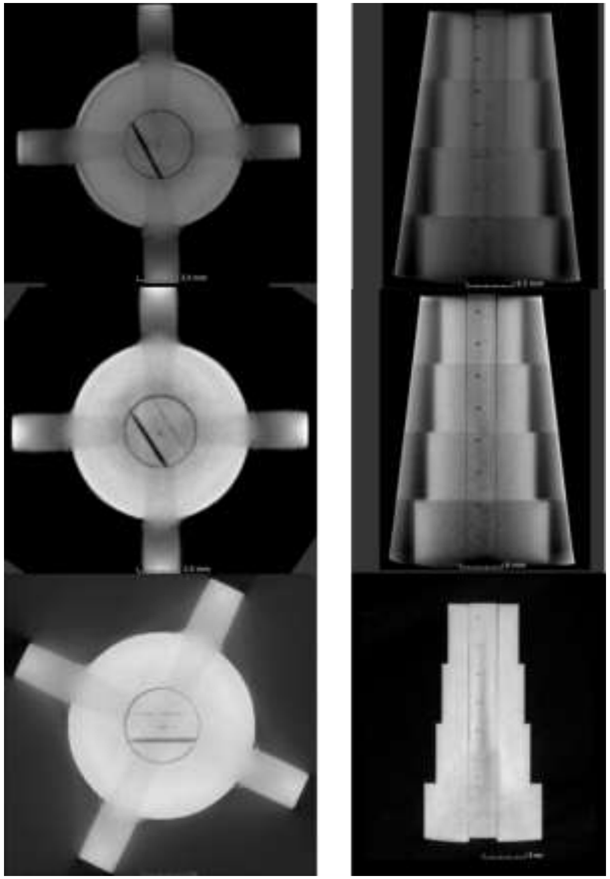






ASTM Round Robin Testing Illustrative Results

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



n-perfluorodecalin screening liquid, standard resolution CT

no screening liquid, standard resolution CT

no screening liquid, high resolution CT

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:

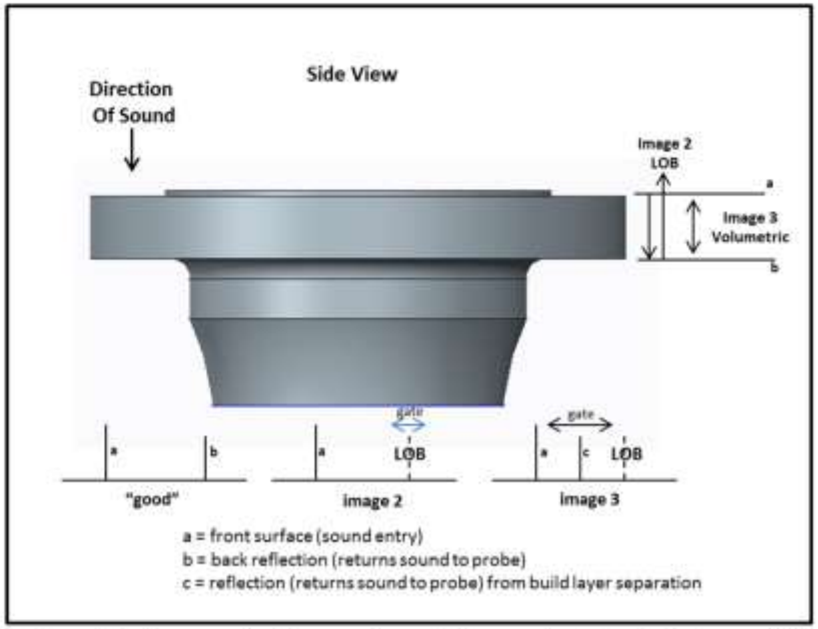
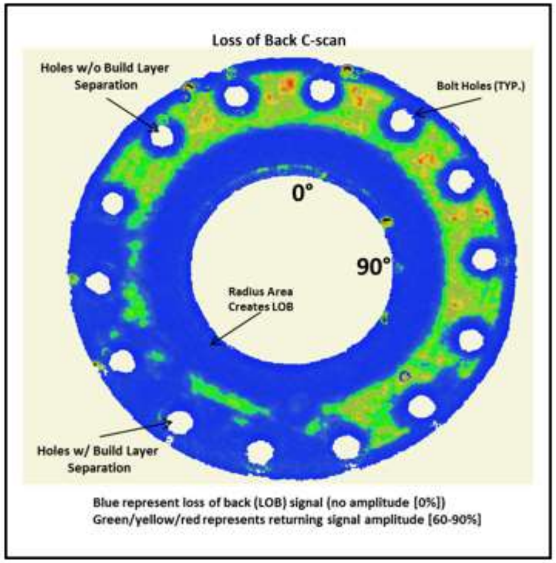
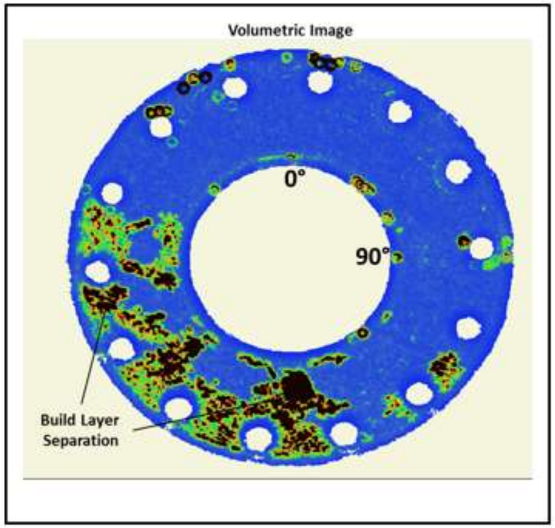


FIG. 14.1 Schematic diagram showing an ultrasonic immersion test of a flange with the build layers at 90° to the sound path.



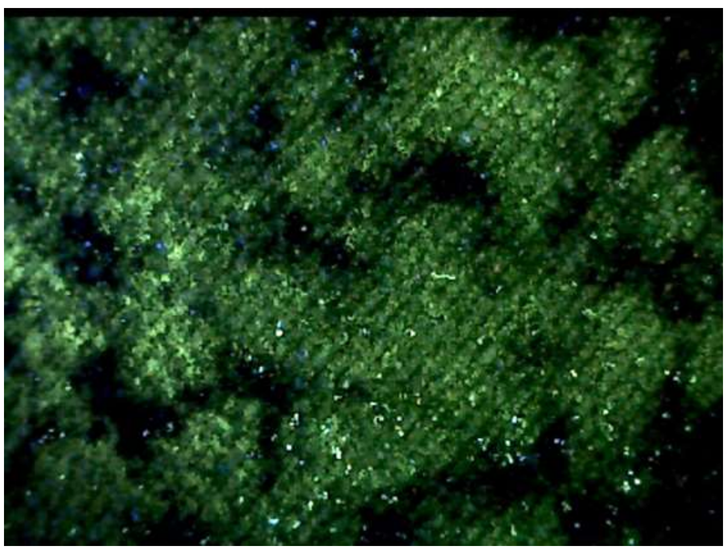


Ultrasonic immersion test image of a flange (top) showing the correlation of areas with **loss of back reflection with areas of build layer separation** determined by a volumetric c-scan (bottom).

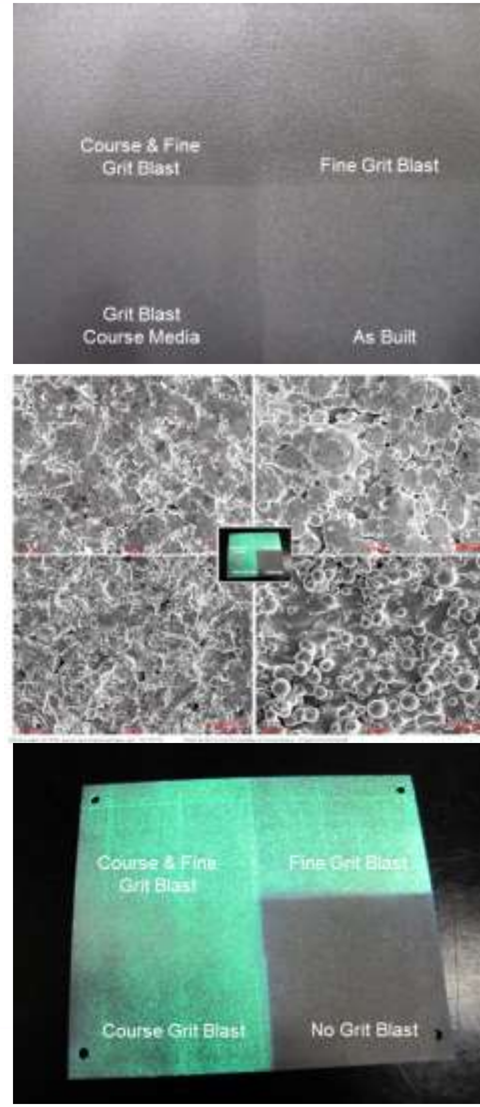
PT of AM parts:

Pratt & Whitney
A United Technologies Company
Pratt & Whitney Rocketdyne

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.



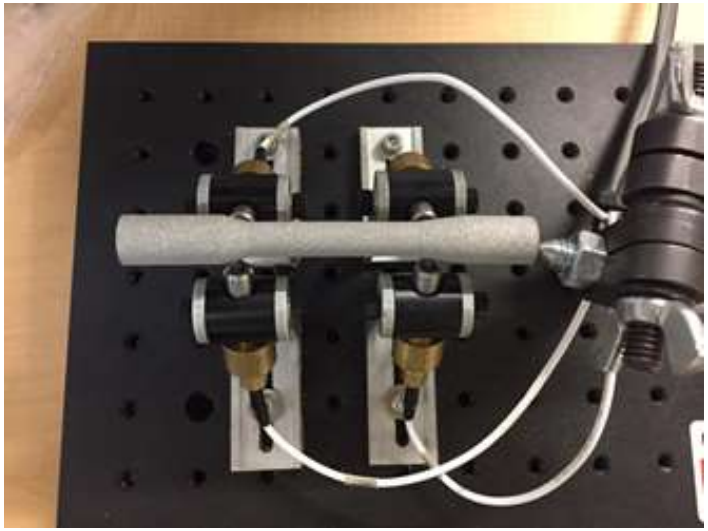
50× view of a surface holding penetrant



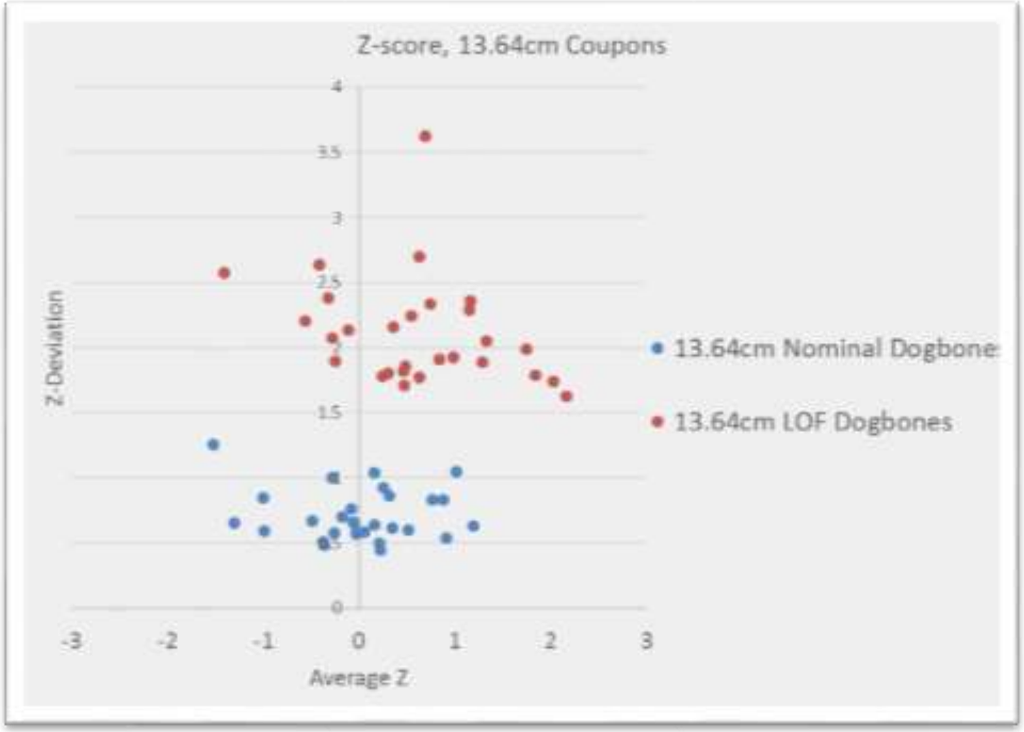
Effect of sand grit blasting on PT results: visible images (top), 200× micrographs (middle), and UV images of grit-blasted surfaces with penetrant applied (bottom)

September 2017 Webmeeting Round Robin Sample Activity

Vibrant 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)



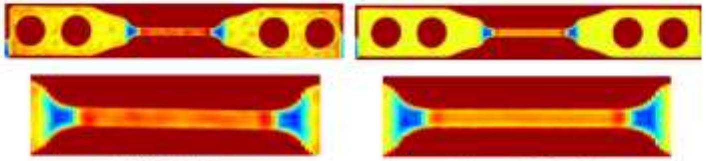
PASS/FAIL testing using Mahalanobis-Taguchi System (MTS) scores

September 2017 Webmeeting Round Robin Sample Activity (cont.)

SOUTHERN RESEARCH

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).

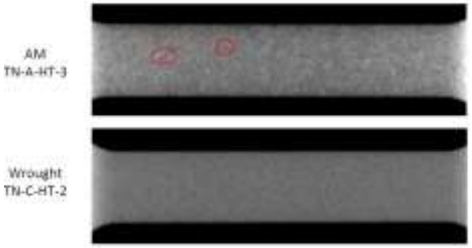
UT

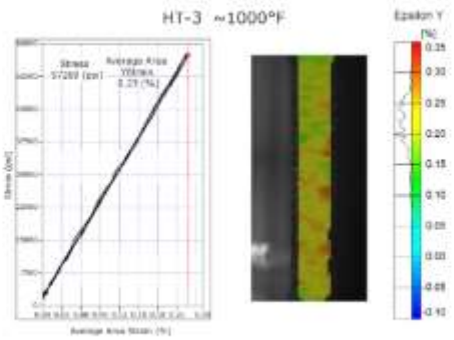


AM C-Scan Map

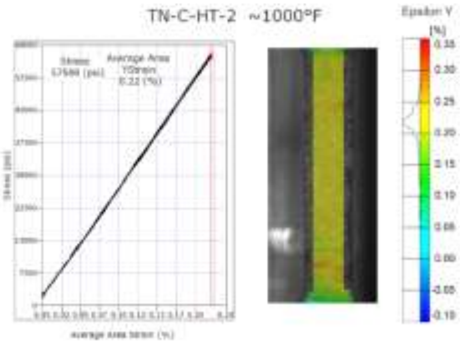
Wrought C-Scan Map

RT





AM Strain Field Visualization
Max Load (500#)



Wrought Strain Field Visualization
Max Load (500#)

high temperature DIC

measure Poisson's ratio, CTE, and modulus

ASTM E07.10 WK47031 Round Robin Testing Online Collaboration Area

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

ASTM E07.10 WK47031 Round Robin Test Results

Draft report posted on ASTM WK47031 Collaboration Area (188 pp.)

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.)

July 2015

released
October 18, 2017

Qualification & Certification/NASA MSFC Guidance

MSFC-STD-3716

MEASUREMENT SYSTEM IDENTIFICATION METRIC/SI (ENGLISH) UNITS

National Aeronautics and Space Administration

MSFC-STD-3716
BASELINE
EFFECTIVE DATE: October 18, 2017

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

EM20

MSFC TECHNICAL STANDARD

STANDARD FOR ADDITIVELY MANUFACTURED SPACEFLIGHT HARDWARE BY LASER POWDER BED FUSION IN METALS

Approved for Public Release; Distribution is Unlimited

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

MSFC-SPEC-3717

MEASUREMENT SYSTEM IDENTIFICATION METRIC/SI (ENGLISH) UNITS

National Aeronautics and Space Administration

MSFC-SPEC-3717
BASELINE
EFFECTIVE DATE: October 18, 2017

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EM20

MSFC TECHNICAL STANDARD

SPECIFICATION FOR CONTROL AND QUALIFICATION OF LASER POWDER BED FUSION METALLURGICAL PROCESSES

Approved for Public Release; Distribution is Unlimited

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

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

Contains **procedures** for implementing the foundational requirements in 3716:

- Qualified Metallurgical Process
- Equipment Control
- Personnel Training

NASA MSFC Engineering and Quality Standard and Specification

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


MEASUREMENT SYSTEM IDENTIFICATION METRIC/SI (ENGLISH) UNITS

National Aeronautics and Space Administration

MSFC-SPEC-3717
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CHECK THE MASTER LIST — VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

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/NASA Approach

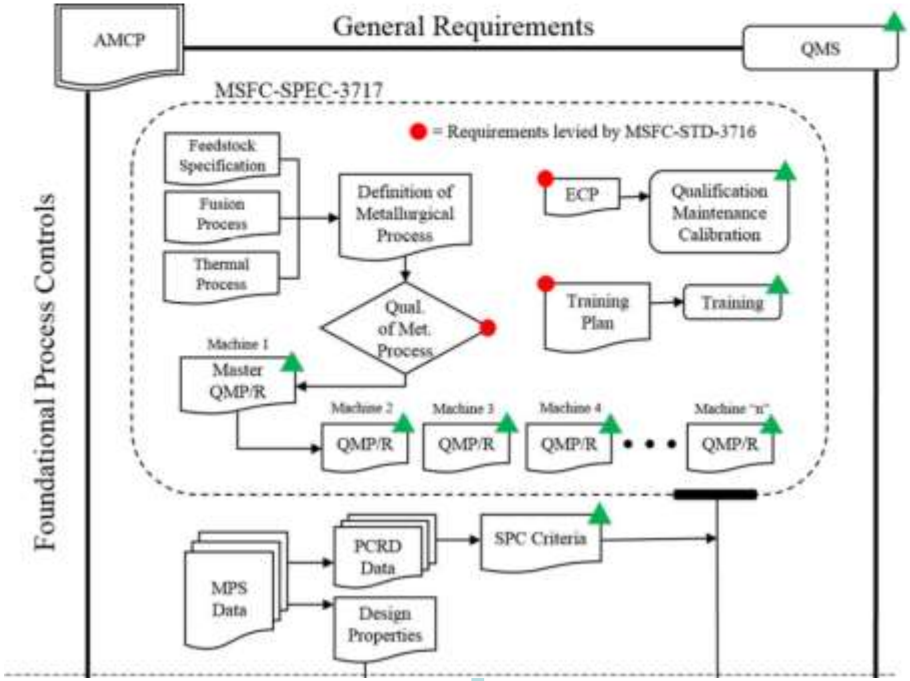
Certification is the affirmation by the program, project, or other reviewing authority that the verification and validation process is complete and has adequately assured the design and as-built hardware meet the established requirements to safely and reliably complete the intended mission.

Certification process has two parts:

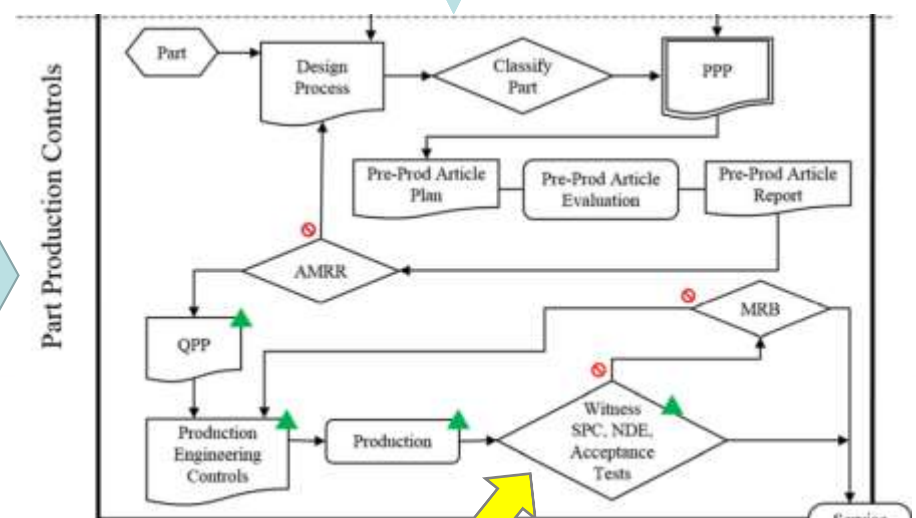
Design Certification:
Design certification is a stand-alone event that typically occurs at the completion of the design process, but prior to use, or following a significant change to the design, understanding of environments, or system behavior.

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

- ▲ Identifies key points of QMS involvement.
- ● Identifies PBF requirements levied by MSFC-STD-3716 with procedures in MSFC-SPEC-3717
- ⊘ Negative outcome of decisional action

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

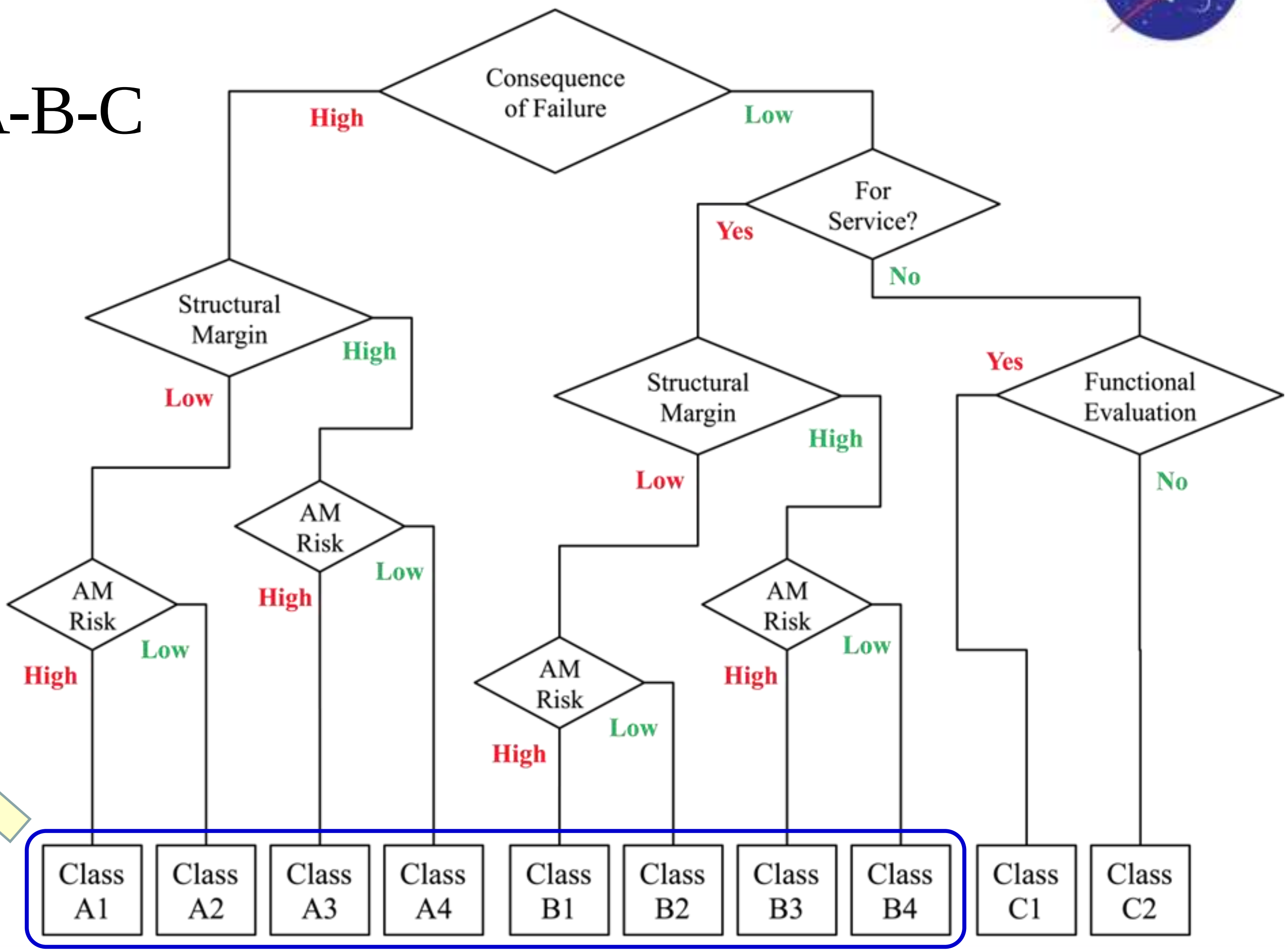
QMP = Qualified Metallurgical Process (foundational control)
- A range of controls covering powder feedstock, process parameters, post-processing, and final detail and rendering

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 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.

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:

Additive Manufacturing Risk	Yes	No	Score
All critical surface and volumes **can be reliably inspected**, or the design permits **adequate proof testing** based on stress state?	0	5	
As-built surface **can** be fully removed on all fatigue-critical surfaces?	0	3	
Surfaces interfacing with sacrificial supports **are fully accessible** and improved?	0	3	
Structural walls or protrusions are ≥ 1mm in cross-section?	0	2	
Critical regions of the part **do not** require sacrificial supports?	0	2	
		Total	

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.

1. **Class III** **High – Flight-critical - primary structure**
    - Structural, Primary loads, Full Environmental, Safety of Flight
    - Full exposure to operational loads and environment
    - Quality of workmanship inspection Dimensional Analysis of mating and critical surfaces, Form, Fit and Function compatibility
    - Parts ***shall*** require X-Ray, CT or Laser Scanning, Proof (Tensile) Loading, Micro-Structure, Density, Porosity, Chemistry of First Article part.
    - Thermal, Shock/Vibration, Environmental and Program Specific testing ***are*** required to validated process and design.
2. **Class III** **Medium – Flight - secondary structure**
    - Secondary Structure, Multiple Load Paths, Partial Environment, High Margins
    - Limited exposure to operational loads and environment. Dimensional Analysis may include CM, mating and critical surfaces, Quality of workmanship inspection.
    - Parts ***may*** require X-Ray, CT or Laser Scanning, Proof (Tensile) Loading, Micro-Structure, Density, Porosity, Chemistry of First Article part.
    - Thermal, Shock/Vibration, Environmental and Program Specific testing ***may be*** required to validated process and design.
3. **Class II** **Support – Non-structural**
    - Limited exposure to environmental conditions
    - Ground station, Lab environment, test equipment
    - Limited Dimensional Analysis: mating and critical surfaces only – Quality of workmanship inspection
4. **Class 1** **Low – Non-critical**
    - Non-structural, No consequence of failure, No Mission Impact
    - Working prototypes/models
    - Quality of workmanship inspection
5. **Class 1** **Prototype/Models**
    - Engineering use only
    - Form, Fit, Function, concept parts
    - Visual inspection

Purpose of MSFC-STD-3716 Standard

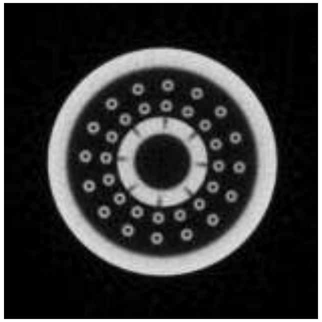
- Since PBF processes have not yet had the benefit of years engineering experience by NASA, its contractors, or third-party OEMs, undiscovered failure modes are likely to remain.
- MSFC-STD-3716 offers a conservative approach to existing NASA requirements by treating AM as an evolving process subject 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:

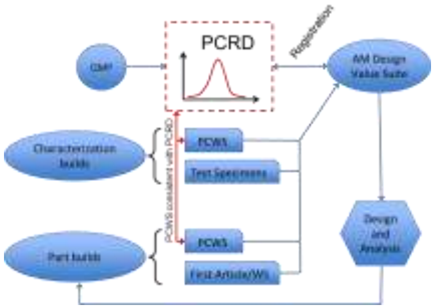
Qualified Metallurgical Process (QMP)

Equipment Control Plan (ECP)

Training Plan (including control of vendors)



Part Production Plan (PPP)

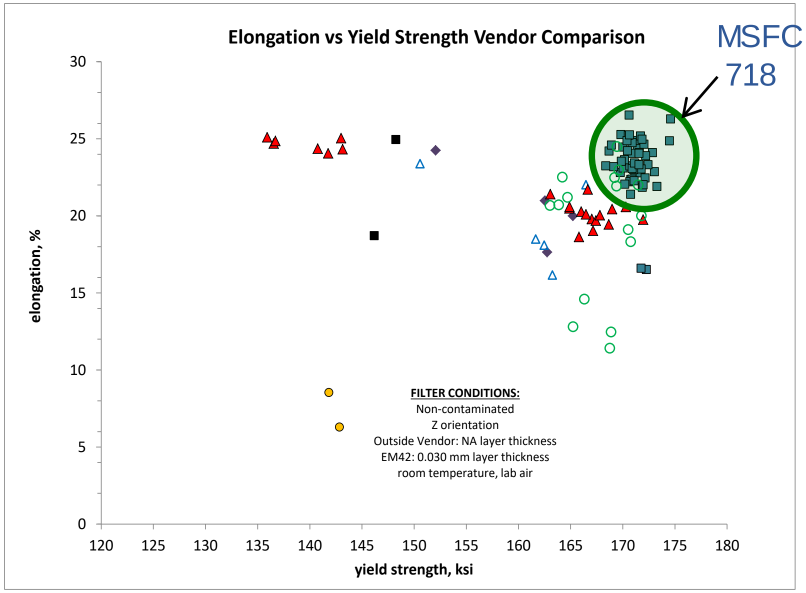


Statistical Process Control (SPC)

- 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.

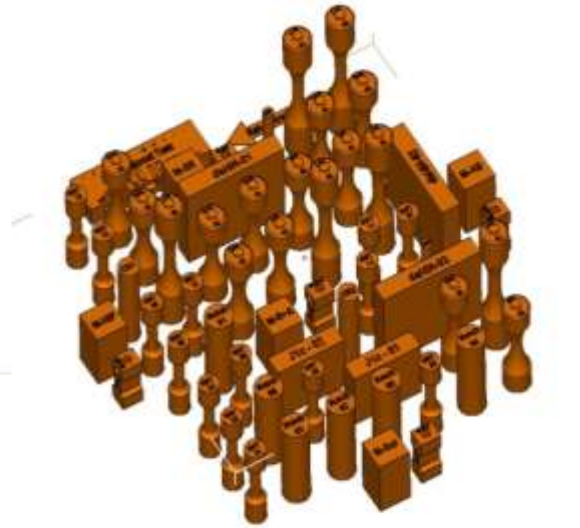
Metal AM Product Variability§

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.

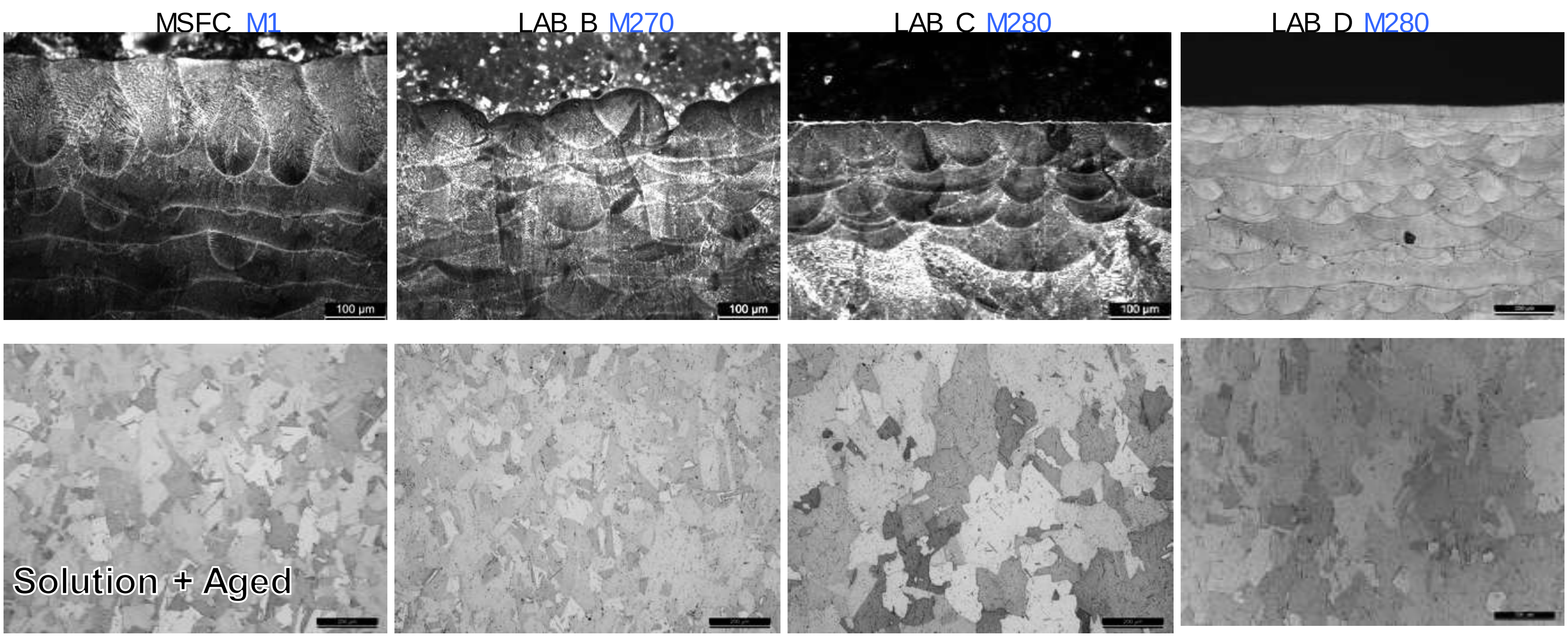
LAB	OEM	Model	Power (W)	Speed (mm/s)	Hatch (mm)	Layer Thickness (micron)	Rotation Angle
MSFC	CL	M1	180	600	.105	30	90
LAB A	EOS	-	-	-	-	40	-
LAB B	EOS	M270	195	-	-	40	67
LAB C	EOS	M280	305	1010	.110	40	67
Lab D	EOS	M280	285	960	N/A	40	67



§ Brown, A., Jones, Z. Tilson, W., Classification, Effects, and Prevention of Build Defects in Powder-bed Fusion Printed Inconel 718, NASA Marshall Space Flight Center, 2016.

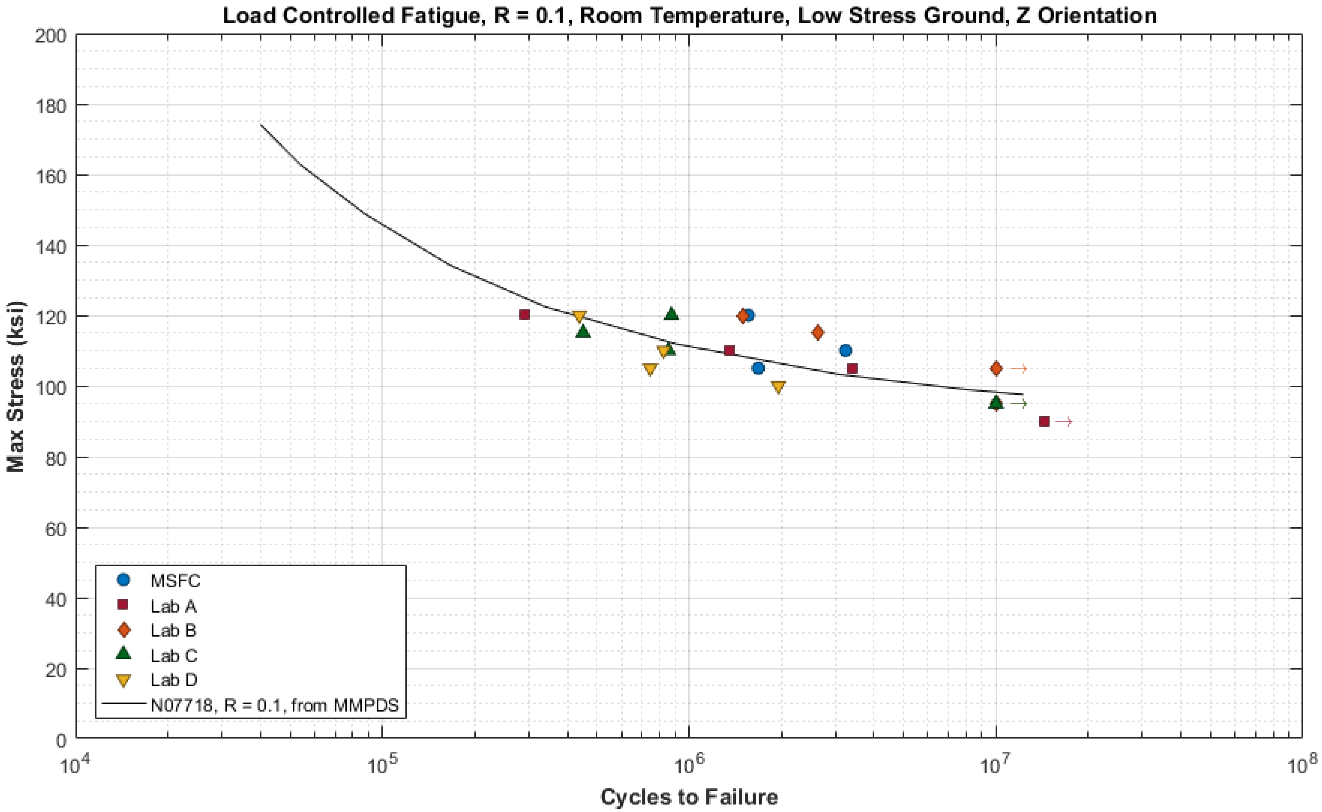
Round Robin: Microstructure

- 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.



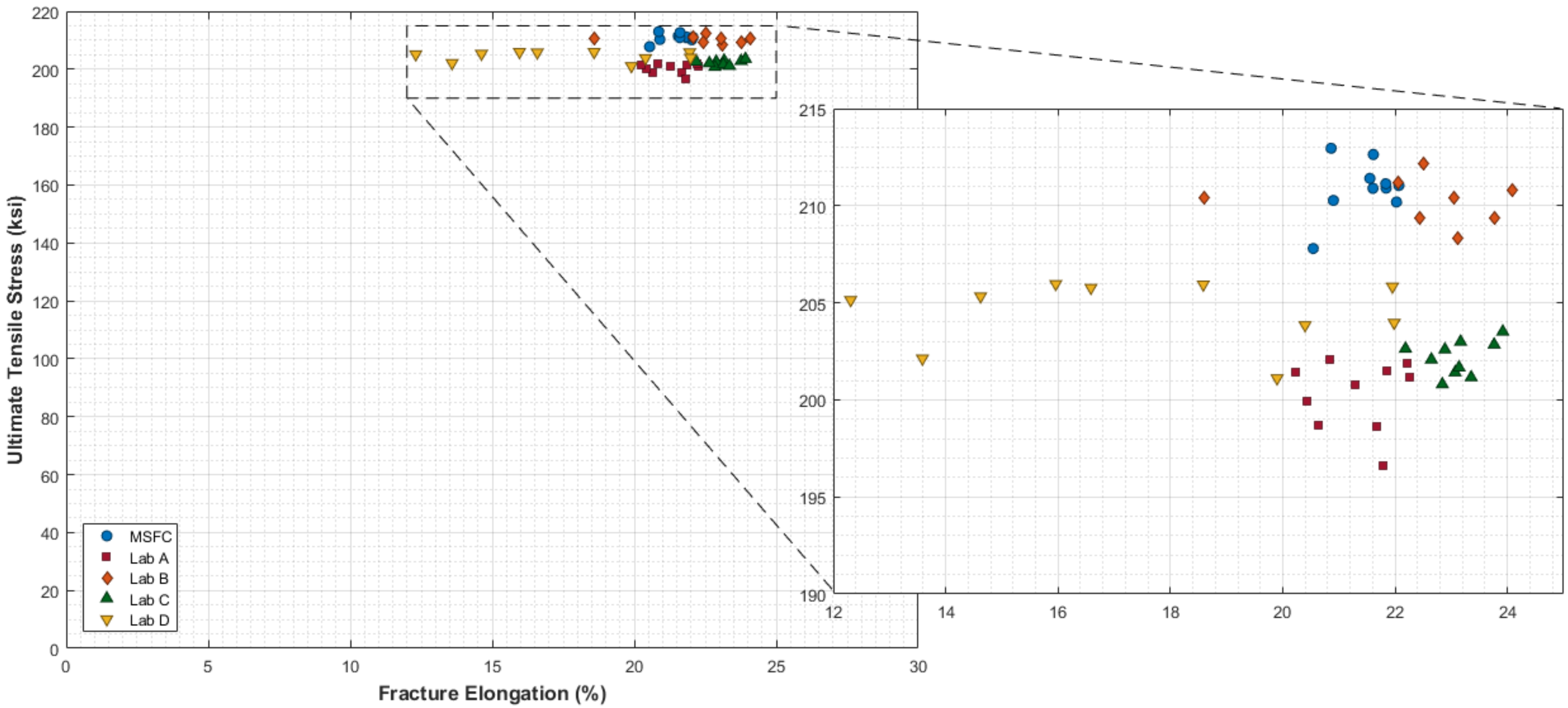
Round Robin: Low Cycle Fatigue

- 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.



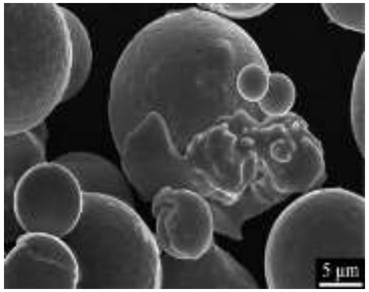
Round Robin: Tensile Properties

- 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.

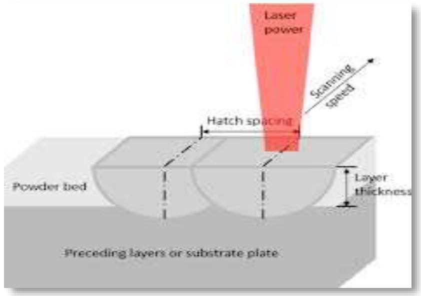


Qualified Metallurgical Process

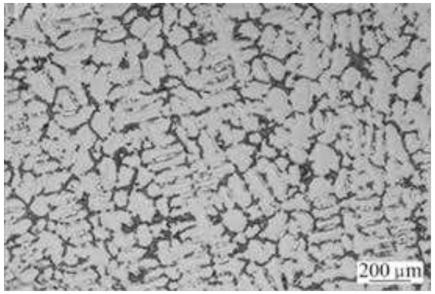
- MSFC-STD-3716 identifies AM as a unique material product form and requires the metallurgical process to be qualified (QMP) on ***every*** individual AM machine
- Developed from internal process specifications with likely incorporation of forthcoming industry standards.



Powder



Process Variables

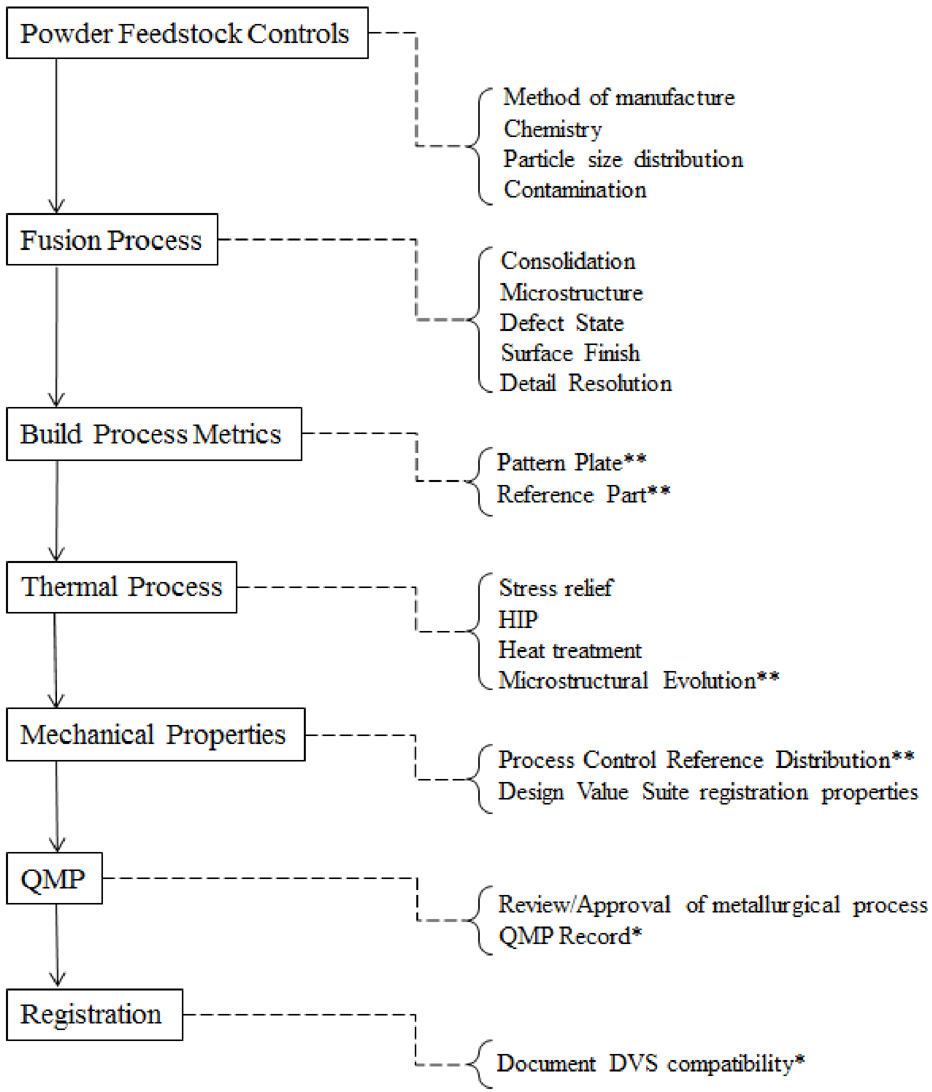


Microstructure

Properties

QMP:

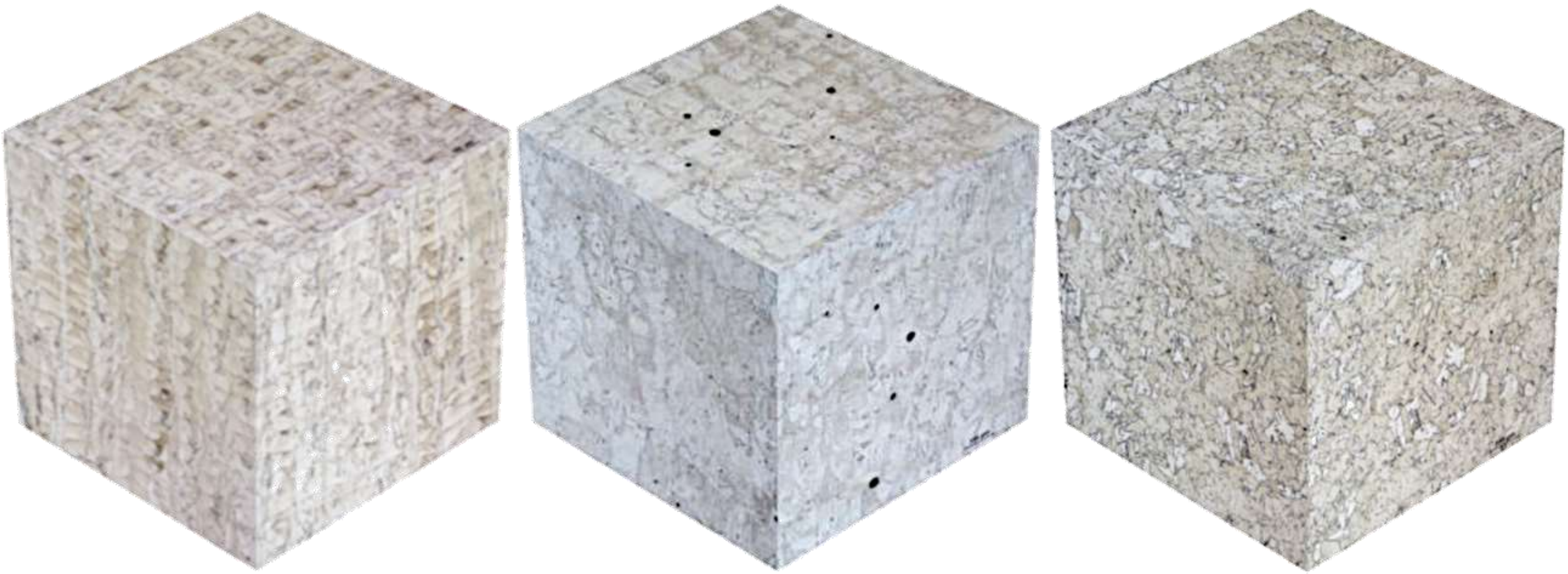
- Feedstock control or specification
- AM machine parameters, configuration, environment
- As-built densification, microstructure, and defect state
- Control of surface finish and detail rendering
- Thermal post-processing for controlled microstructural evolution
- Mechanical behavior reference data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



*Quality management system record
**Acceptance criteria metric

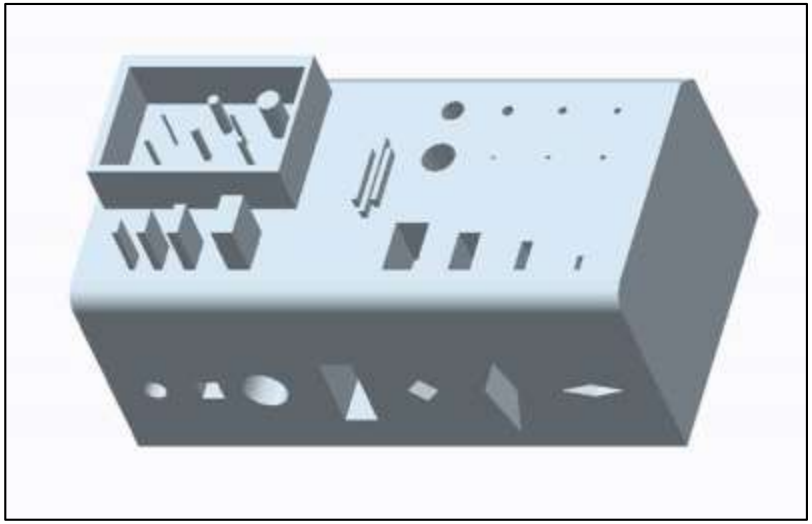
Qualified Metallurgical Process (QMP)

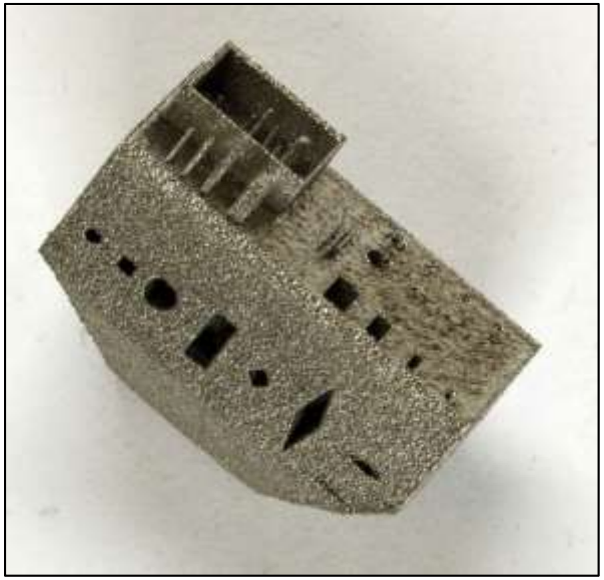
- As-built densification, microstructure, and defect state
- Thermal process for controlled microstructural evolution



Qualified Metallurgical Process (QMP)

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





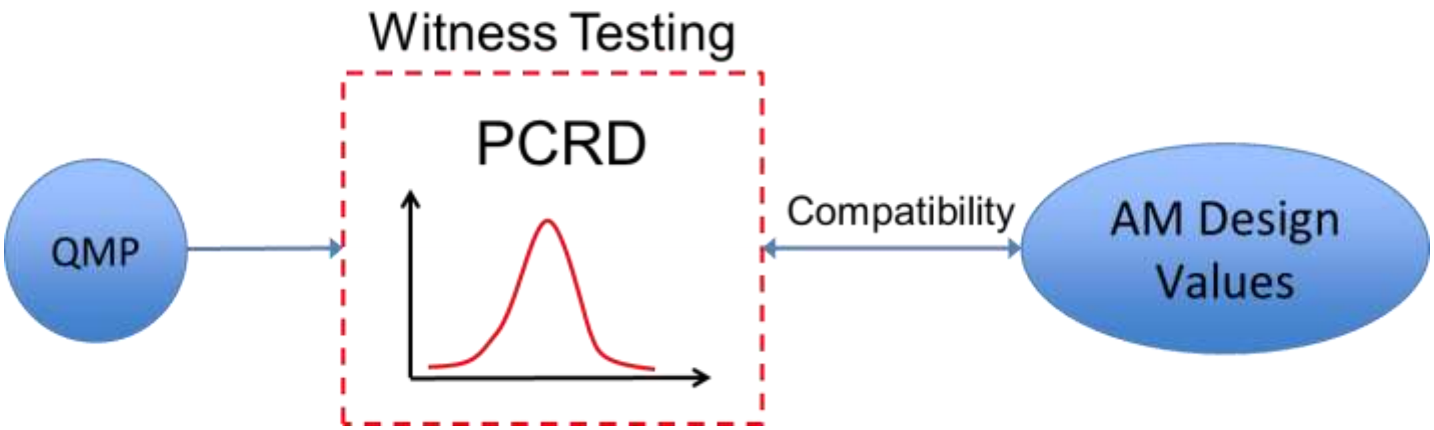
Reference parts:

Metrics for surface texture quality and detail rendering

Overhanging, vertical and horizontal surface texture, acuity of feature size and shape

Qualified Metallurgical Process

- Mechanical behavior reference data
  - Strength, ductility, fatigue performance
  - Process Control Reference Distributions (PCRD)
- Establish and document estimates of mean value and variation associated with mechanical performance of the AM process per the QMP
  - May evolve with lot variability, etc.
- Utilize knowledge of process performance to establish meaningful witness test acceptance criteria



AM Qualification Challenges

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

Concept Laser X-line Material Mill in a Box

- **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
ace defects within the limitations of technique and part geometry.
incumbent upon the structural assessment community to define
cal initial flaw sizes (CIFS) for the AM part to define the
ctives of the NDE.
wledge of the CIFS for AM parts will allow the NDE and fracture
rol communities to evaluate risks and make recommendations
rding the acceptability of risk.
S defects shall be detected at the accepted probability of detection
D), e.g., 90/95, for fracture critical applications.
E demonstration parts with simulated CIFS defects are used to
onstrate NDE detection capability.
nonstration of adequate part life starting from NASA-STD-
9 flaw sizes is generally inappropriate for fracture critical,
nage tolerant AM parts.
Class A parts, NDE indications of cracks, crack-like defects, or
r findings of undetermined source should be elevated to senior
ew and disposition per applicable fracture control policy.

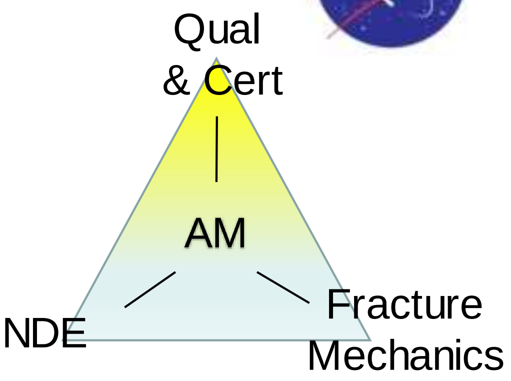
Spaceflight Hardware NDE Considerations

- 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

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?

Or a great place to get involved even if you've been doing this for a while

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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

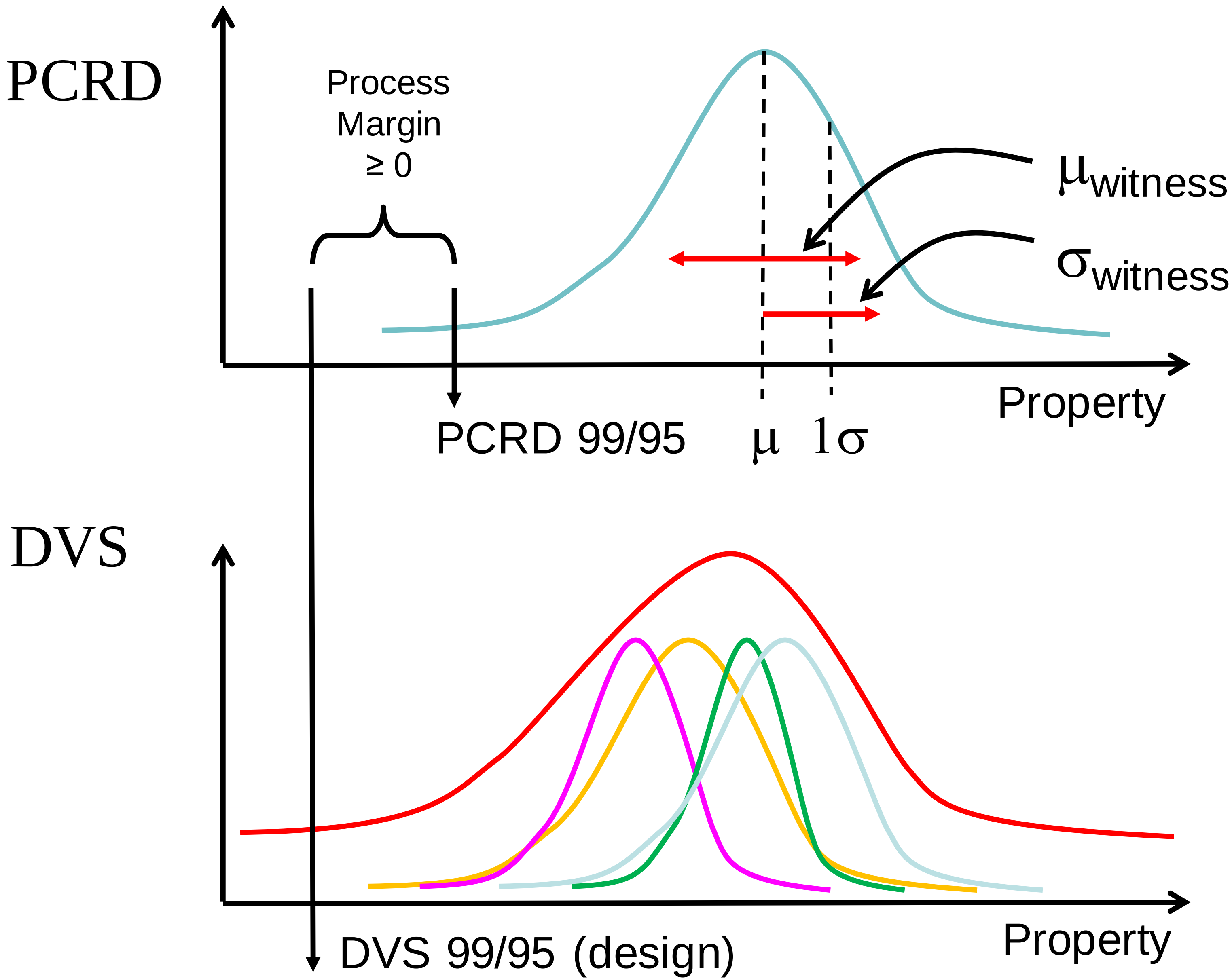
Mechanical Property Witness Procedures

- 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**

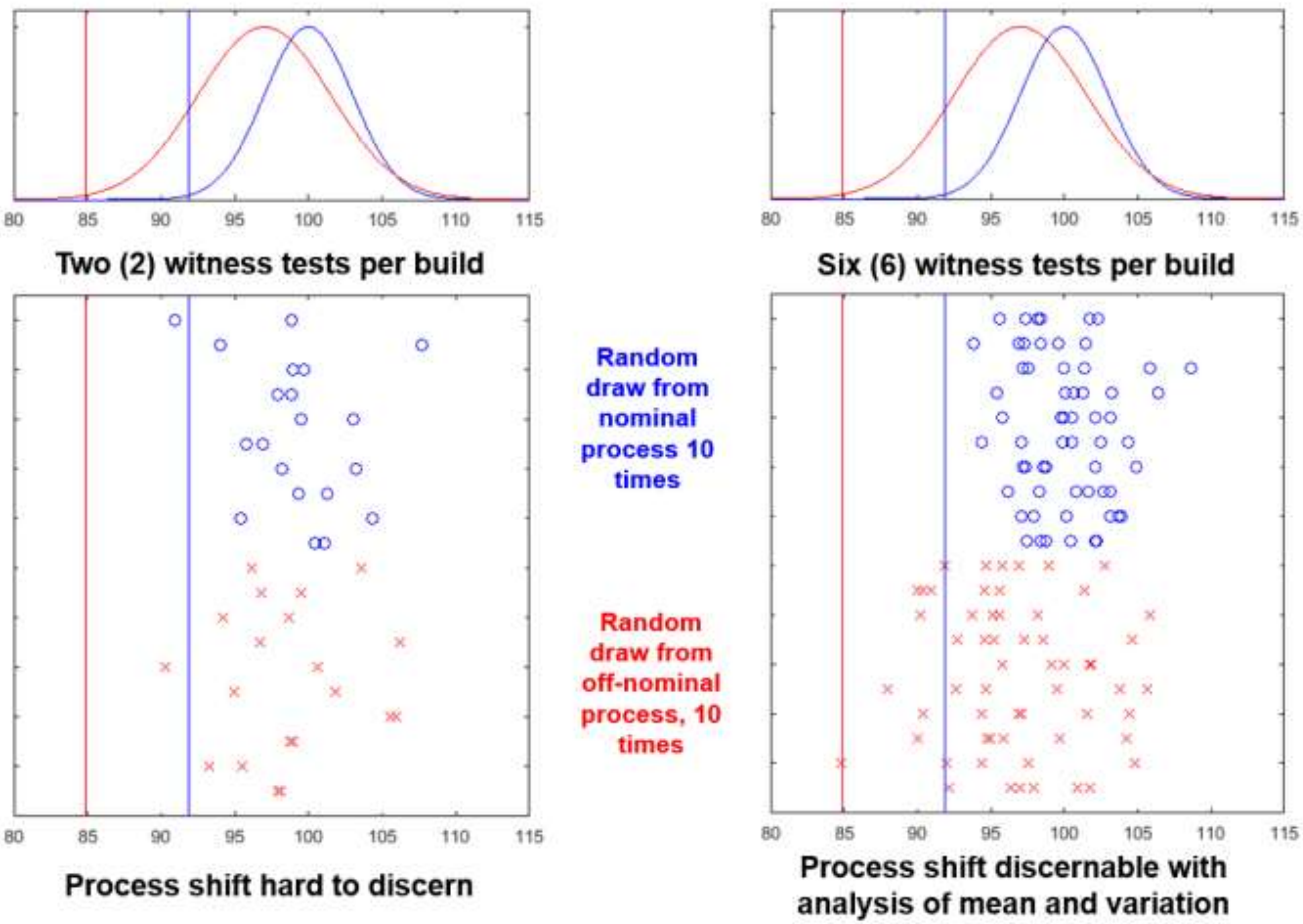
Qualification & Certification/Qualified Metallurgical Process



Certification/Witness for Statistical Process Control

Example of AM build witness specimen evaluations

Nominal process is blue, off nominal in red

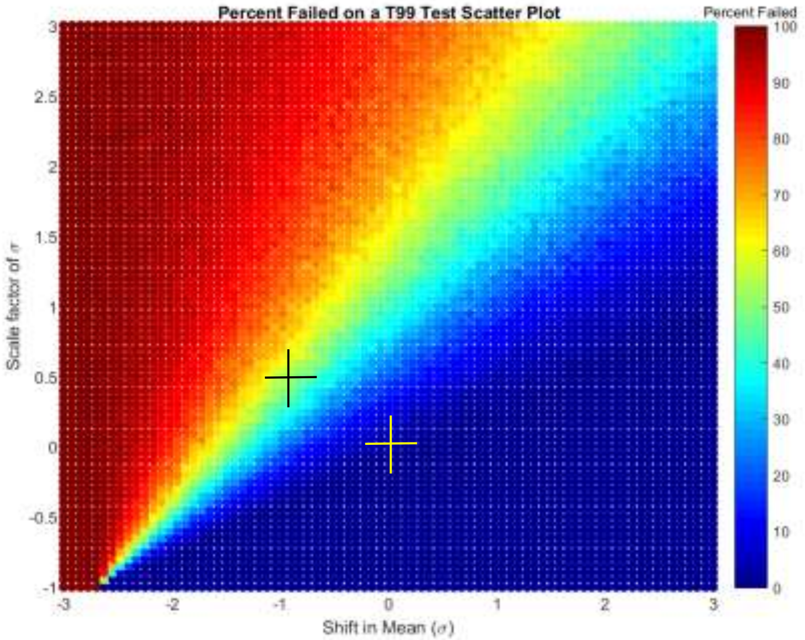


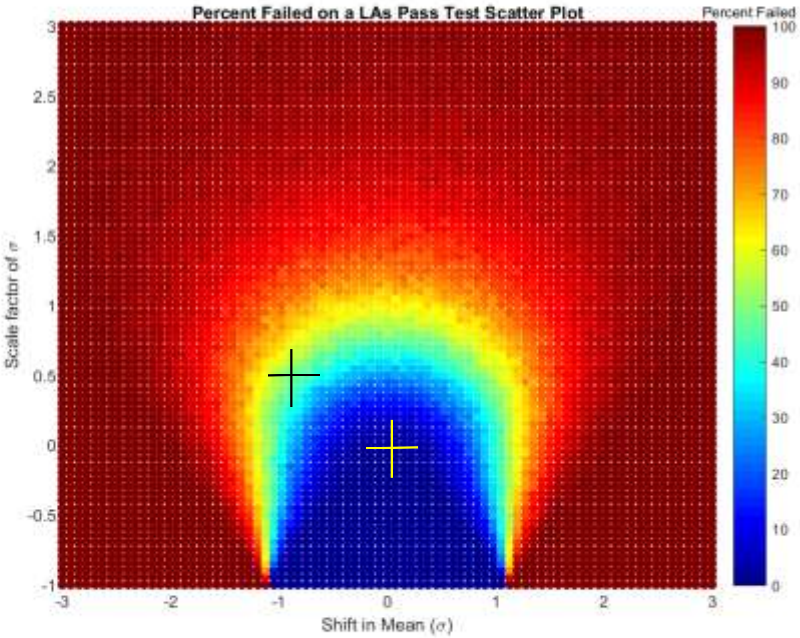
Qualification & Certification/Witness for Statistical Process Control

Simulation is used to evaluate small sample statistical methods for witness specimen acceptance.

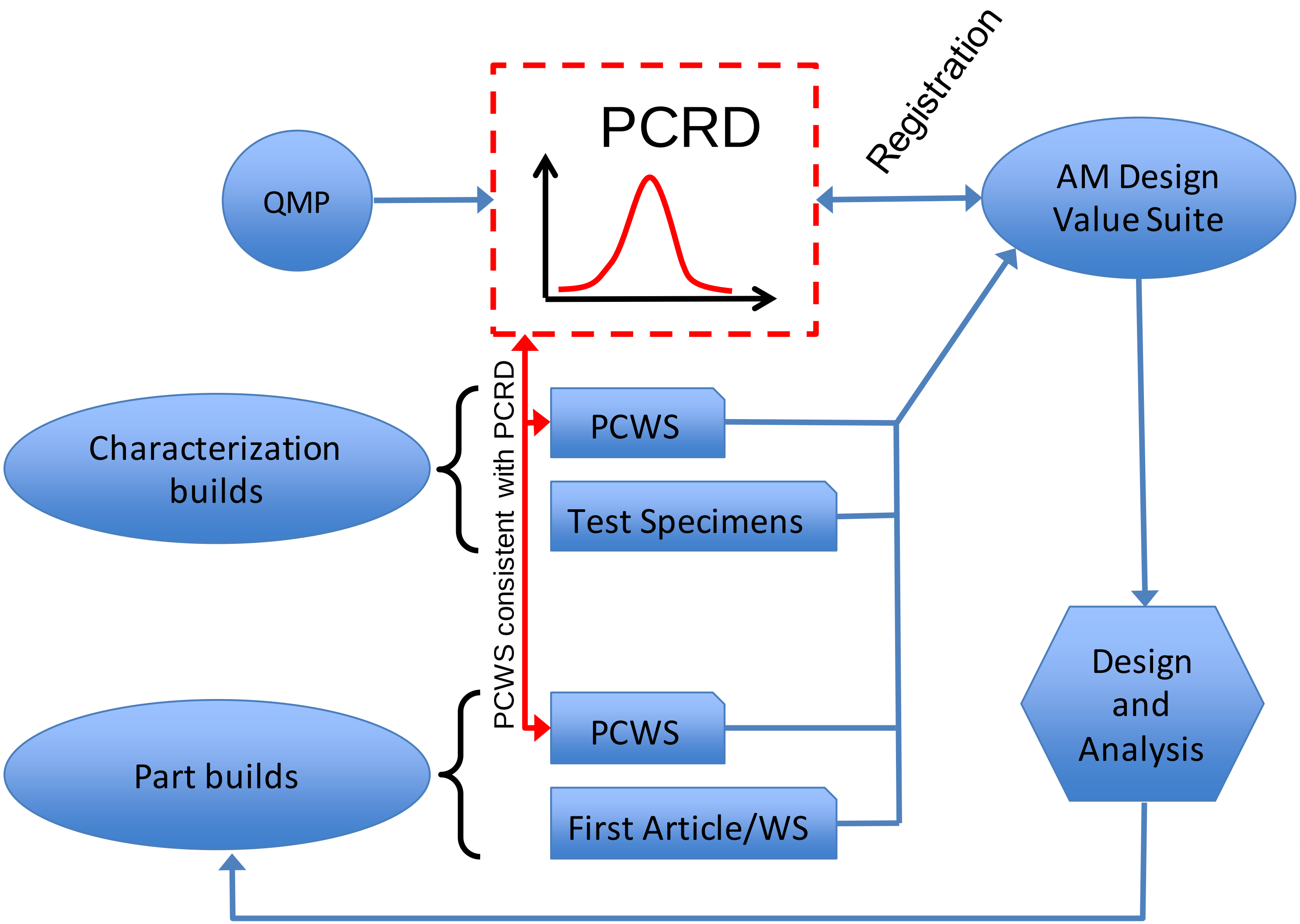
Design acceptance criteria for the following:

- 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



Qualification & Certification/Summary of Points

- **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