NDE and Inspection Challenges for Additively Manufactured Components

Jess M. Waller ♦ NASA-JSC WSTF

NRC Additive Manufacturing Public Meeting
Session 4

Tuesday, Nov. 28, 2017
1330 Eastern Time
UTC-05:00

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**.

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

Using traditional manufacturing methods, 163 individual parts would be made and then assembled. But with 3D printing technology, **fewer parts** (2) were required, saving time and money and allowing engineers to build parts with **enhanced performance** and are **less prone to failure**.

Metallic Aerospace AM Parts – Example 2

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 Snecma. CFM has orders for 6000 LEAPs.

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 5X higher durability vs. conventional manufacturing.

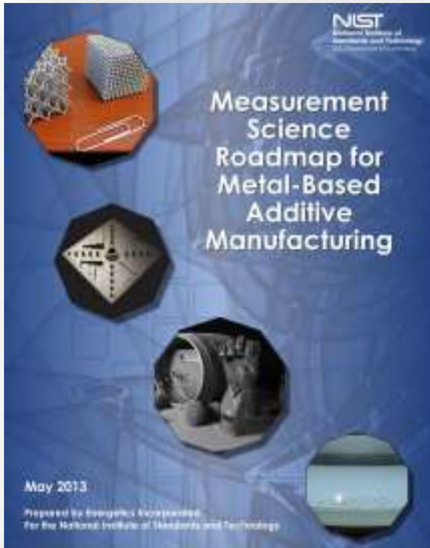
GE Leap Engine fuel nozzle. CoCr material fabricated by direct metal laser melting (DMLM), GE's acronym for DMLS, SLM, etc.

"*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*."

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.

Key Documents to Improve Reliability and Safety of Metal AM Parts


NIST

Measurement Science Roadmap for Metal-Based Additive Manufacturing

May 2013

Prepared by Energetics Incorporated
For the National Institute of Standards and Technology


AFRL-RX-WP-TR-2014-0162

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

EWI

JUNE 2014
Interim Report

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
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UNITED STATES AIR FORCE

NASA
Additive Manufacturing
Roadmap and NDE-related
Technology Gaps


NASA/TM—2014-218560

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

Prepared for

November 2014


EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

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

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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

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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

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Marshall Space Flight Center, Alabama 35812

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MSFC TECHNICAL STANDARD

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

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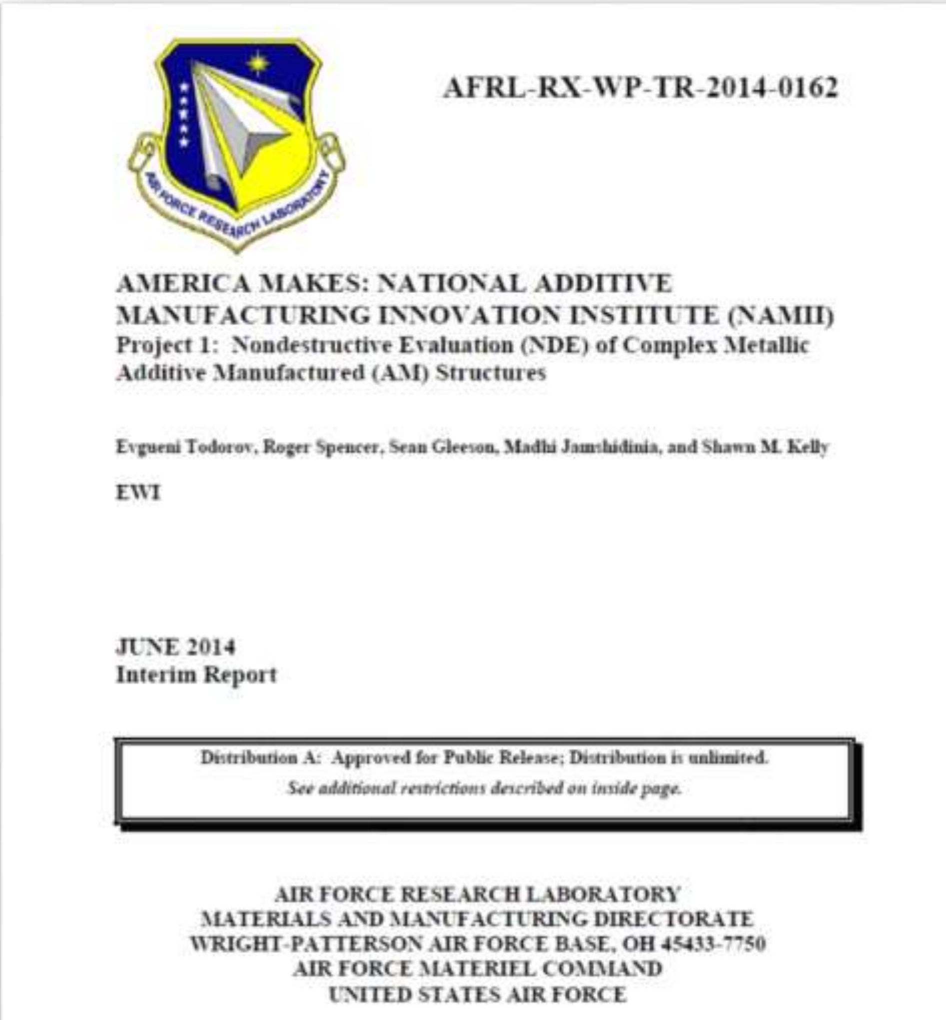
USAF/AFRL-RX-WP-TR-2014-0162 NDE of Complex AM Structures



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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

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Contact: *Evgueni Todorov (EWI)*

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

Effect of AM Part Complexity on NDE

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

1

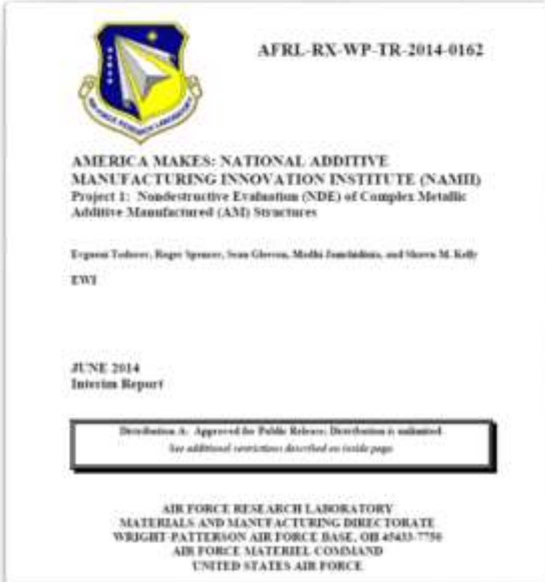
2

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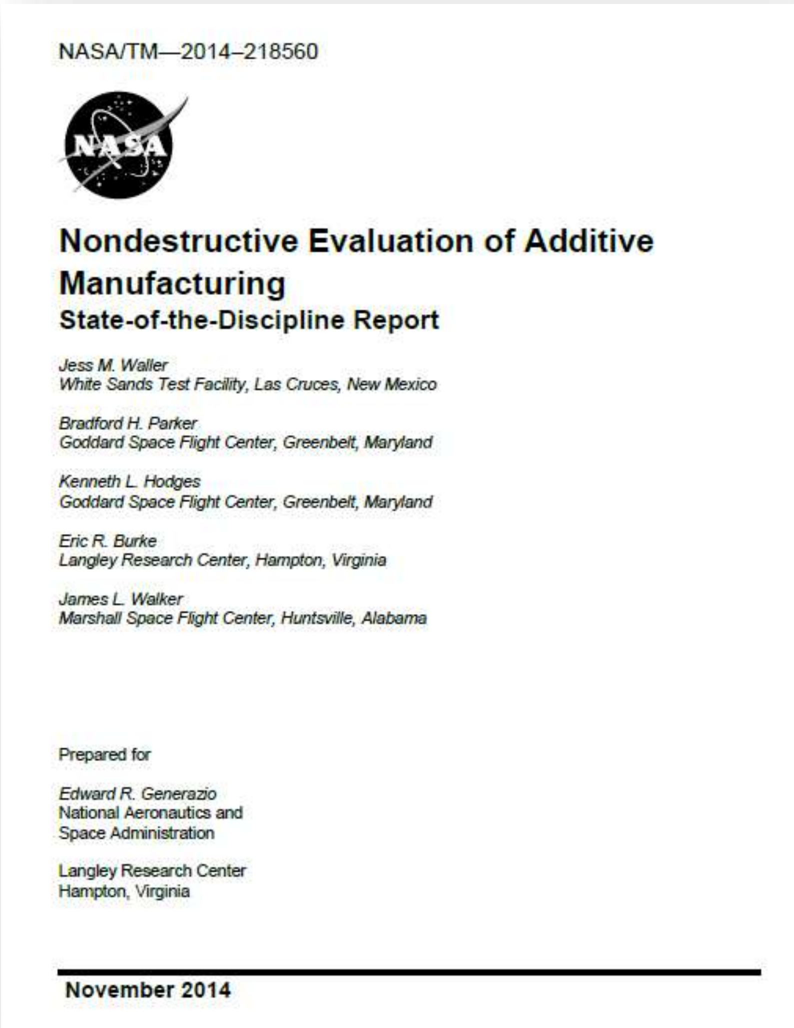
NDE Technique	Geometry Complexity Group					Comments
	1	2	3	4	5	
VT	Y	Y	P(c)	NA	NA	
LT	NA	NA	Y	Y	NA	Screening
PT	Y	Y	P(a)	NA	NA	
PCRT	Y	Y	Y	Y	Y	Screening; size restrictions (e.g., compressor blades)
EIT	Y	Y	NA	NA	NA	Screening; size restrictions
ACPD	Y	Y	P(c)	NA	NA	Isolated microstructure and/or stresses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

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

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

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

§ 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

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November 2014

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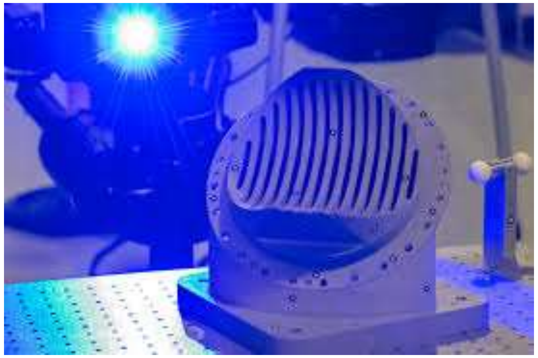
- Industry, government and academia were asked to share their NDE experience on AM parts.
- NDE state-of-the-art was documented.
- **NASA Agency efforts catalogued** through 2014.
- NIST and USAF additive manufacturing roadmaps were surveyed and a **technology gap analysis performed**.

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

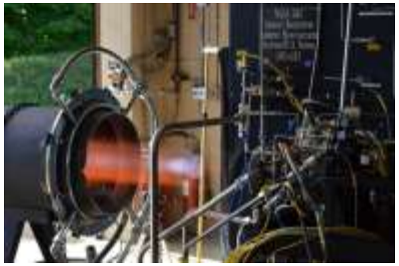
EBF^3 wire-fed system during parabolic fight testing

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

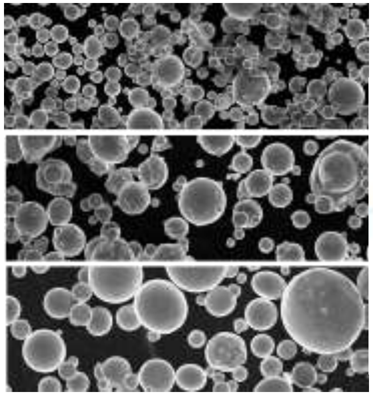
JPL Mars Science Laboratory Cold Encoder Shaft fabricated by gradient additive processes

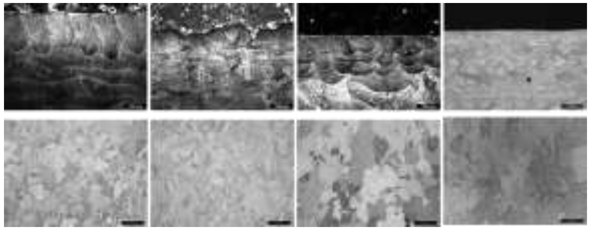
MSFC copper combustion chamber liner for extreme temperature and pressure applications

NASA-sponsored 3-D Printed Habitat Challenge Design Competition

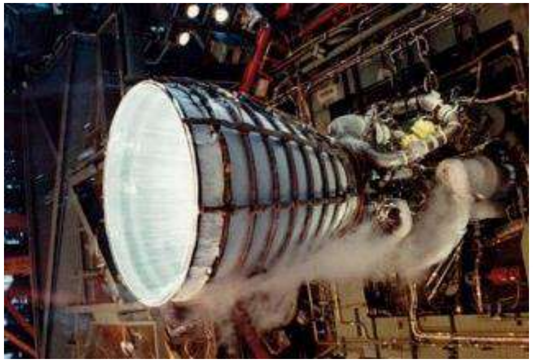
MSFC rocket engine fuel turbopump

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





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



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

NDE-related Technology Gaps:

first
- 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

somewhere in the middle

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

AM challenges for NDE specialist:

- Complex geometry (see AFRL-RX-WP-TR-2014-0162)
- Deeply embedded flaws and internal features
- Rough as-built surface (interferes with PT, ET)
- Variable grain structure or metastable microstructure
- Lack of physical reference standards with same material and processing history as AM parts (demonstrate NDE capability)
- Lack of effect-of-defect studies (use sacrificial defect samples)
- Methods to seed 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
- Little (any?) probability of detection (POD) data
- Lack of written NDE procedures for AM parts (area of focus today)
- Lack of mature in-process monitoring techniques
- Process-specific defects can be produced, some unique to AM

Develop a defect catalogue

- Develop a defects catalogue
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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.

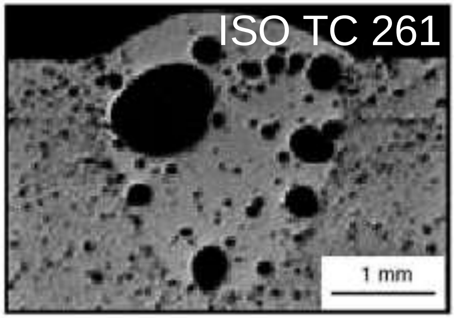
	Flaw type	Non- NDT	Common in DED & PBF	Covered by current standards	Unique to AM
DED	Poor surface finish	■	■		
DED	Porosity		■	■	
DED	Incomplete fusion			■	
DED	Lack of geometrical accuracy/steps in part	■	■		
DED	Undercuts			■	
DED	Non-uniform weld bead and fusion characteristic			■	
DED	Hole or void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

Develop new NDE methods

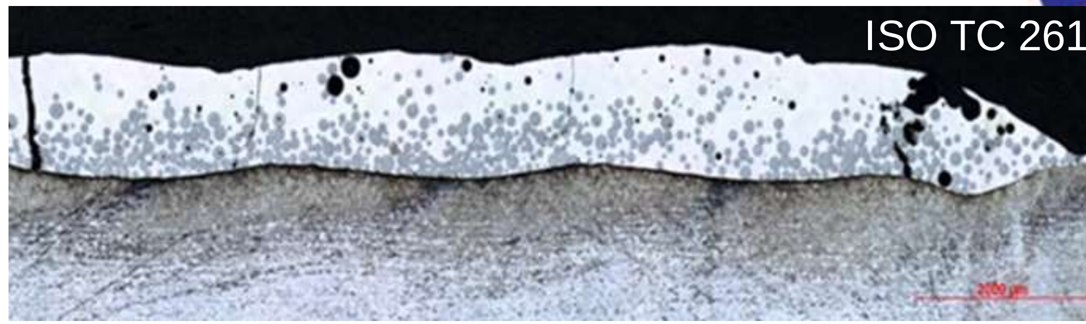
[§] ISO TC 261 JG59, Additive manufacturing – General principles – Nondestructive evaluation of additive manufactured products, under development.

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

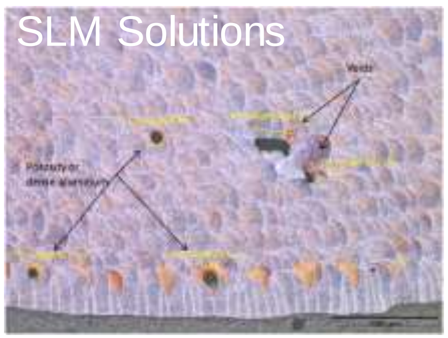
Typical PBF and DED Defects

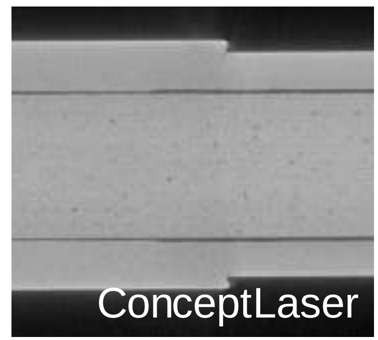


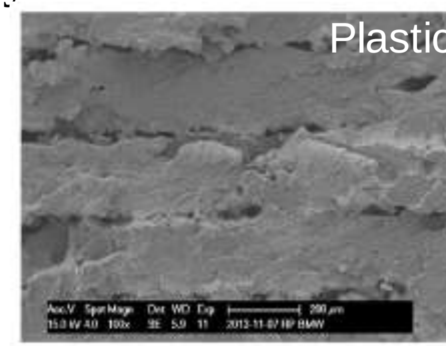
PBF Porosity



DED Porosity







Porosity and Voids

Voids

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

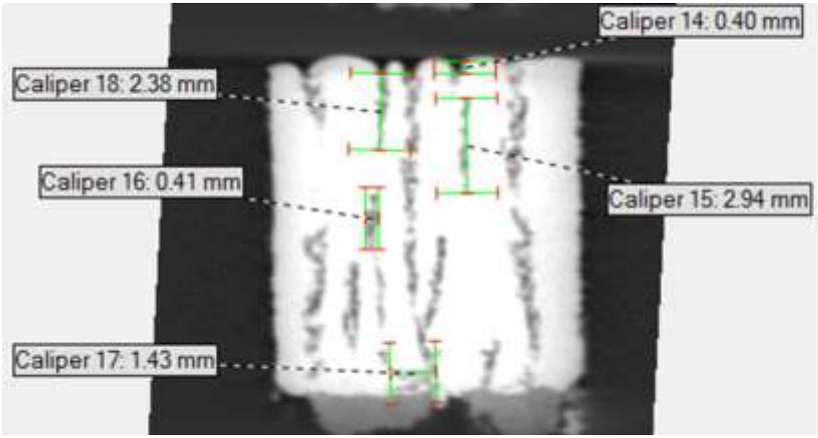
Note: proposed new definitions in ISO/ASTM 52900 Terminology:

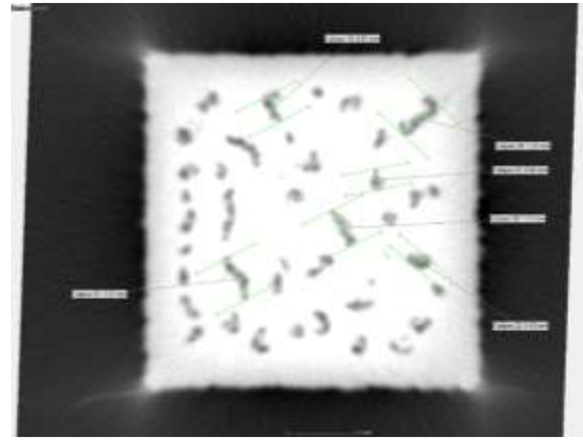
lack of fusion (LOF) *n*—flaws caused by incomplete melting and cohesion between the deposited metal and previously deposited metal.

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.

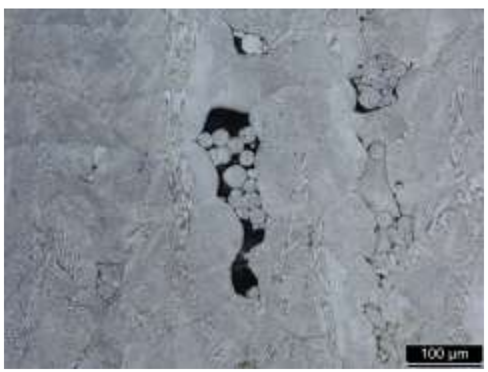
voids, *n*—flaws created during the build process that are empty or filled with partially or wholly un-sintered or un-fused powder or wire creating pockets. Voids are distinct from gas porosity, and are the result of lack of fusion and skipped layers parallel or perpendicular to the build direction. 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.

Typical PBF Defects of Interest

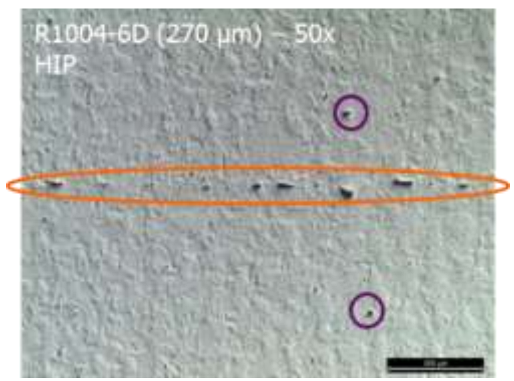




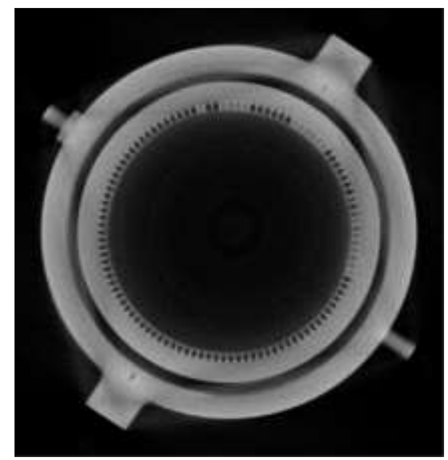
Cross layer



Lack of Fusion (LOF)



Layer



Trapped Powder

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

Use of NDE to Detect Defects of Interest

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).

Defect Causes

- **Bulk Defects**
  - **Lack of Fusion**
    - **Horizontal Lack of Fusion Defect**
      - Insufficient Power
      - Laser Attenuation
      - Spatter
    - **Vertical Lack of Fusion Defect**
      - Large Hatch Spacing
    - Short Feed
  - **Spherical Porosity**
    - Keyhole
  - **Welding Defects**
    - Cracking
- **Surface Defects**
  - **Worm Track**
    - High Energy Core Parameters
    - Re-coater Blade interactions
  - **Core Bleed Through**
    - Small Core Offset
    - Overhanging Surface
  - **Rough Surface**
    - Laser Attenuation
    - Overhanging Surfaces
  - **Skin Separation**
    - Sub-Surface Defects
    - Detached Skin

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

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

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**

NDE of AM
Voluntary Consensus Standards

- Develop a defects catalogue
- Develop in-process NDE to improve feedback control, maximize part quality and consistency, and obtain ready-for-use parts
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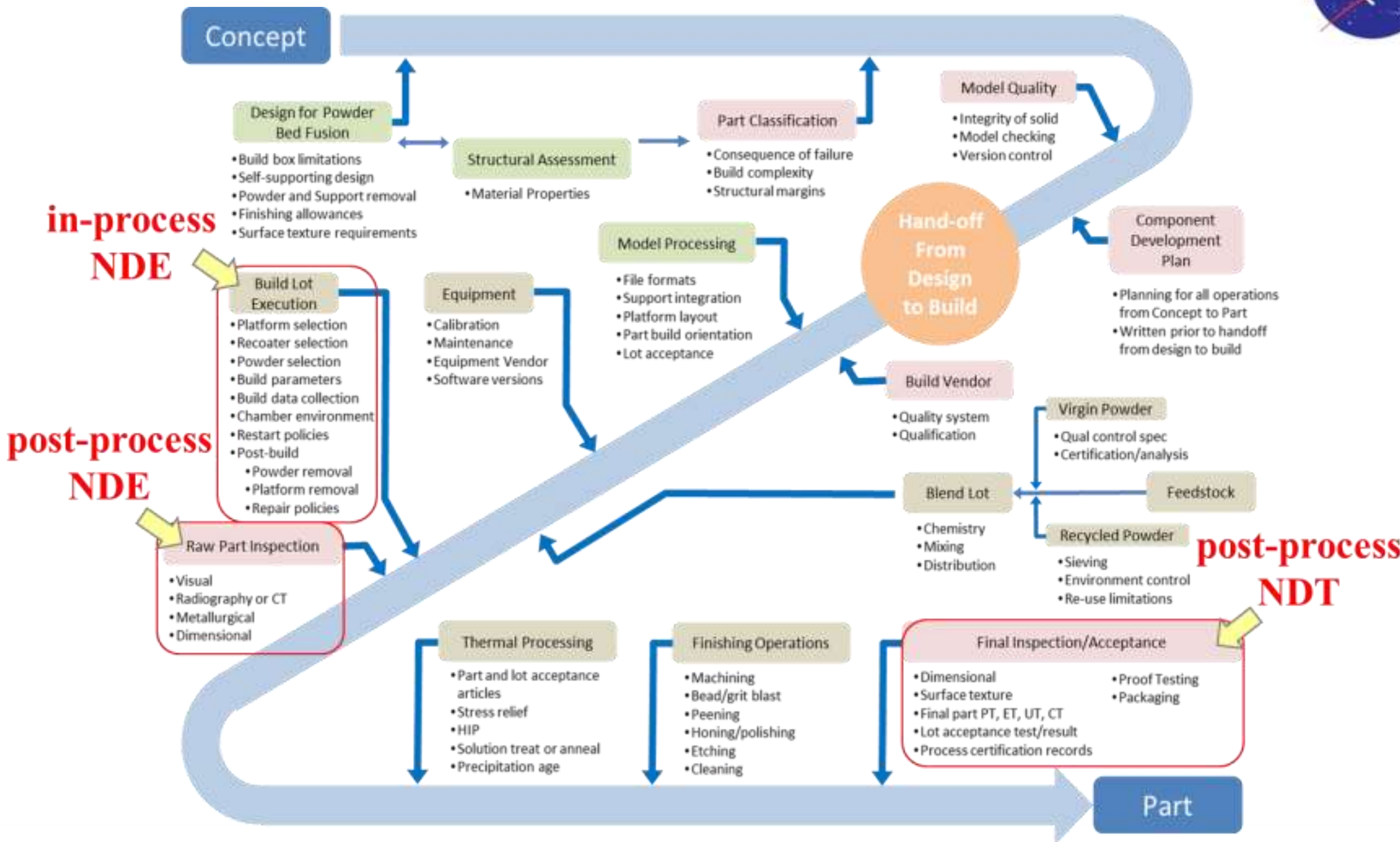
- Apply NDE to understand effect-of-defect, and establish acceptance limits for specific defect types and defect sizes
- Develop NDE-based qualification and certification protocols for flight hardware (screen out critical defects)

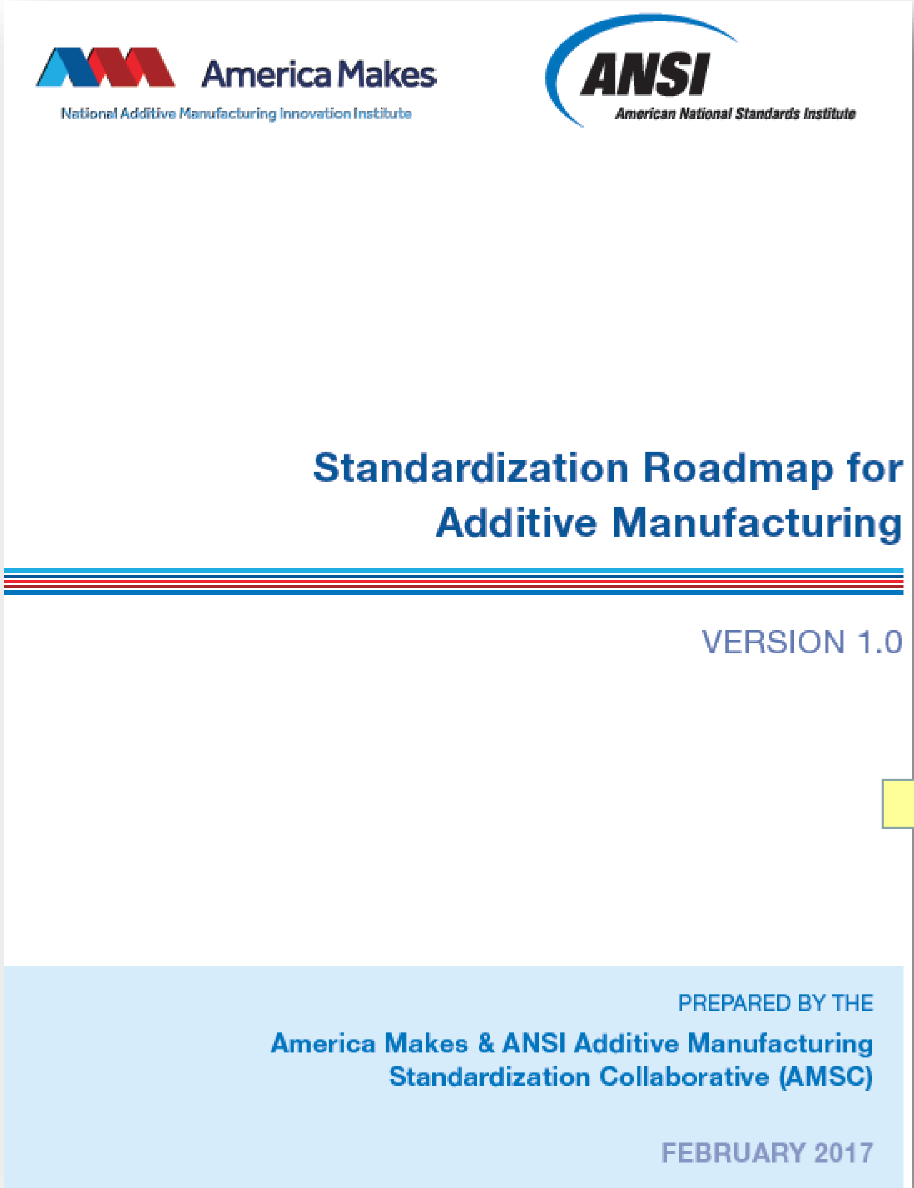
NDE of AM Parts relative to Life Cycle



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

America Makes & ANSI AMSC Roadmap

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


America Makes
National Additive Manufacturing Innovation Institute

ANSI
American National Standards Institute

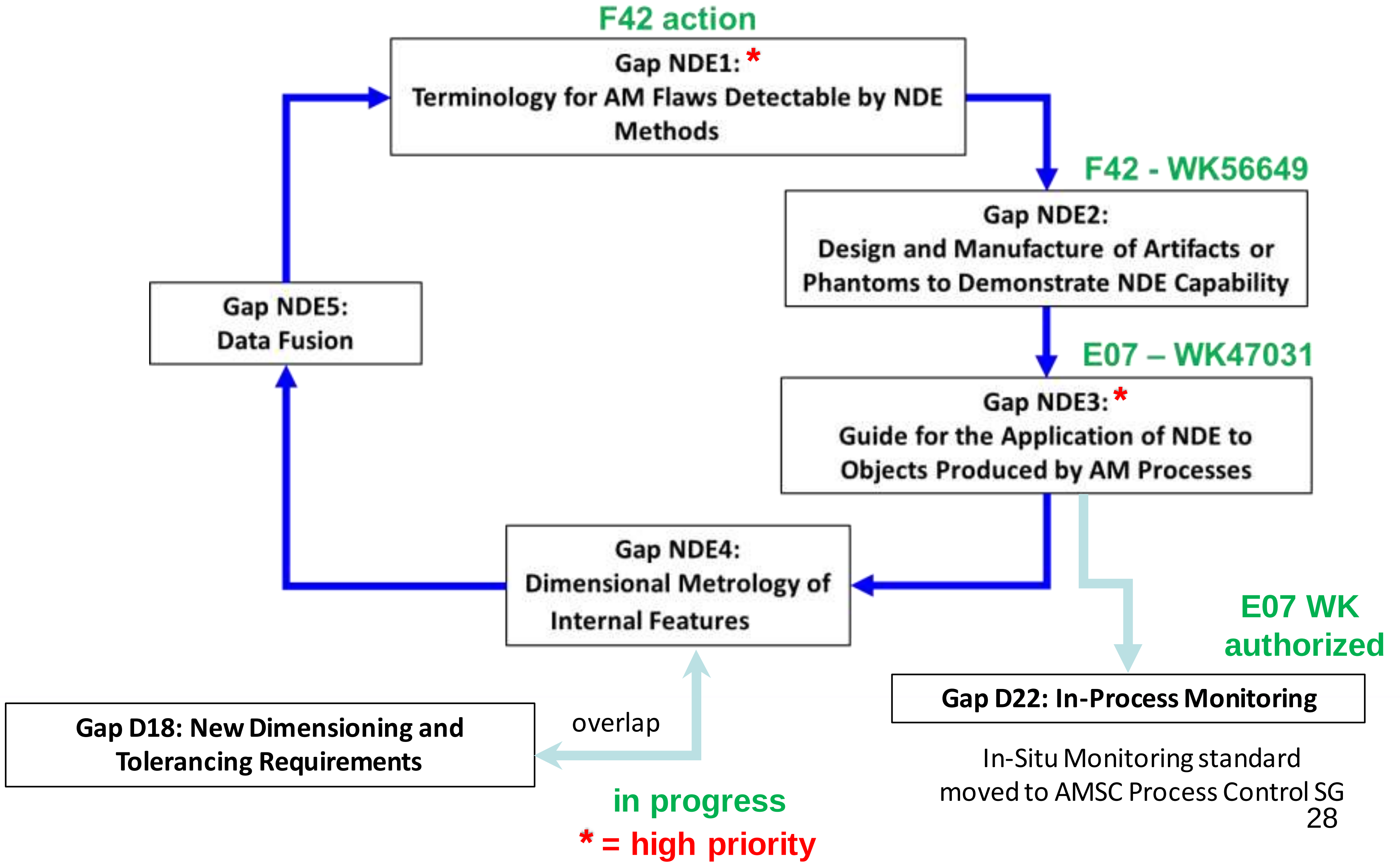
Standardization Roadmap for Additive Manufacturing

VERSION 1.0

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

FEBRUARY 2017

Gaps Identified by NDE Working Group



Gap NDE3: ASTM E07.10 WK47031 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

- ANSI/America Makes AMSC Gap NDE3
- ECT section added
- Re-balloted 7/14/27, closing date 8/14/17
- 1 negative/7 comments being resolved/incorporated

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**)

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ASTM WK56649

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

(What is a Work Item?)

Developed by Subcommittee: F42.01 | Committee F42 | Contact Staff Manager

MORE F42.01 STANDARDS | RELATED PRODUCTS | COPYRIGHT/PERMISSIONS

WK56649

1. Scope

Identify flaw types and provide best practices for reproducing them into the additively manufacturing process for use in the evaluation of 3D metallic printed objects.

Industry does not have a process(s) to identify, create, and evaluate potential anomalies created during the 3D melt/sinter process.

Keywords

flaws; nondestructive testing; nondestructive examination; seeding;

The title and scope are in draft form and are under development within this ASTM Committee.

Recommended
Standards Tracker
Standards Subscriptions

Work Item Status
Date Initiated:
11-17-2016
Technical Contact:
Steve James
Status:
Draft Under Development

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

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**)

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

Gap NDE1: ASTM F42 Terminology for AM Flaws Detectable by NDE

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 for an editorial comparison of defect terms already in ASTM.
- Goal is to use terminology that already exists to save time and effort needed versus developing new definitions.
- F42 and ISO TC 261 are considering balloting of the above terms in the ASTM/SIO 52900 terminology standard, and to put these terms high on the list for consideration.

Round Robin Testing

1) Physical Reference Standards
2) Effect-of-Defect

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

ASTM WK47031 Round Robin Testing

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

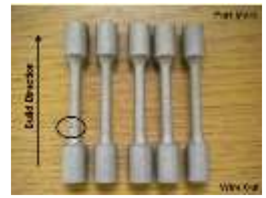
Laser-PBF (L-PBF)

Gong

Ti-6Al-4V bars

Airbus

Al-Si-10Mg dog bones



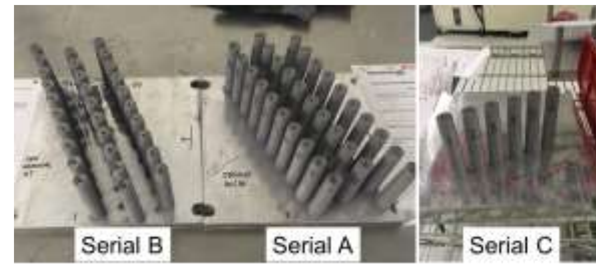
Concept Laser Inconel 718 inserts (6) w/ different processing history

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

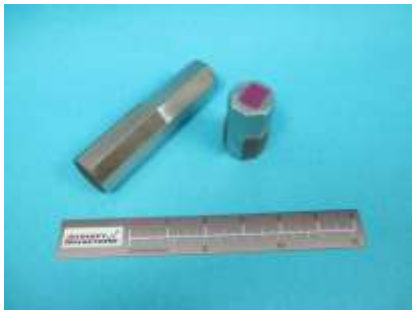
Ti-6Al-4V dogbones

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

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

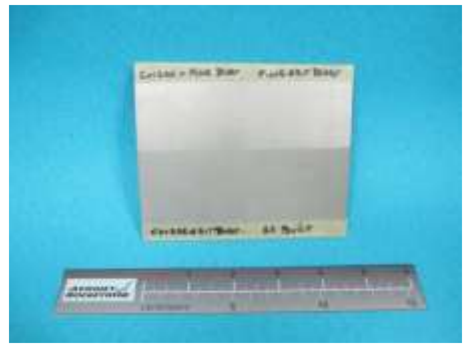
HEX Samples

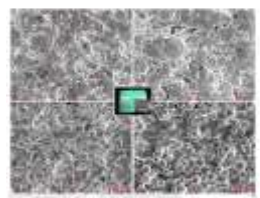
Inconel 718
in two different build orientations



SLM (L-PBF)

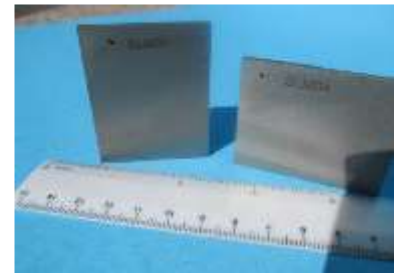
Inconel 625 PT sheets





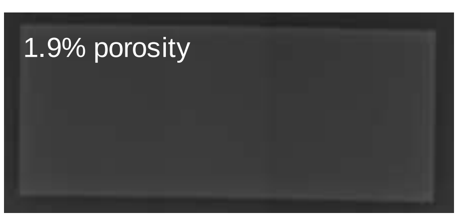
Electron Beam-PBF (E-PBF)

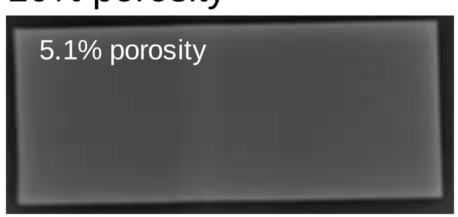
Met-L-Check
SS 316 PT/RT panels
w/ EDM notches



DRDC Porosity Standards

414 steel. 0-10% porosity





Directed Energy Deposition (DED)

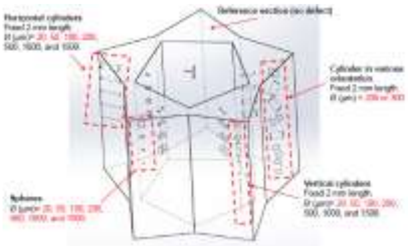
NASA MSFC ABS plastic parts with
optimal and off-optimal settings (T. Prater)

ASTM WK47031 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 Report being compiled by S. James
(post review copy on WK47031 CA in December)

ASTM WK47031 Effort: CT of Concept Laser Samples in North America

CT Round Robin Testing (Previously Evaluated)

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

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

Preplanning – Participation Rules

Samples will be shipped as one set

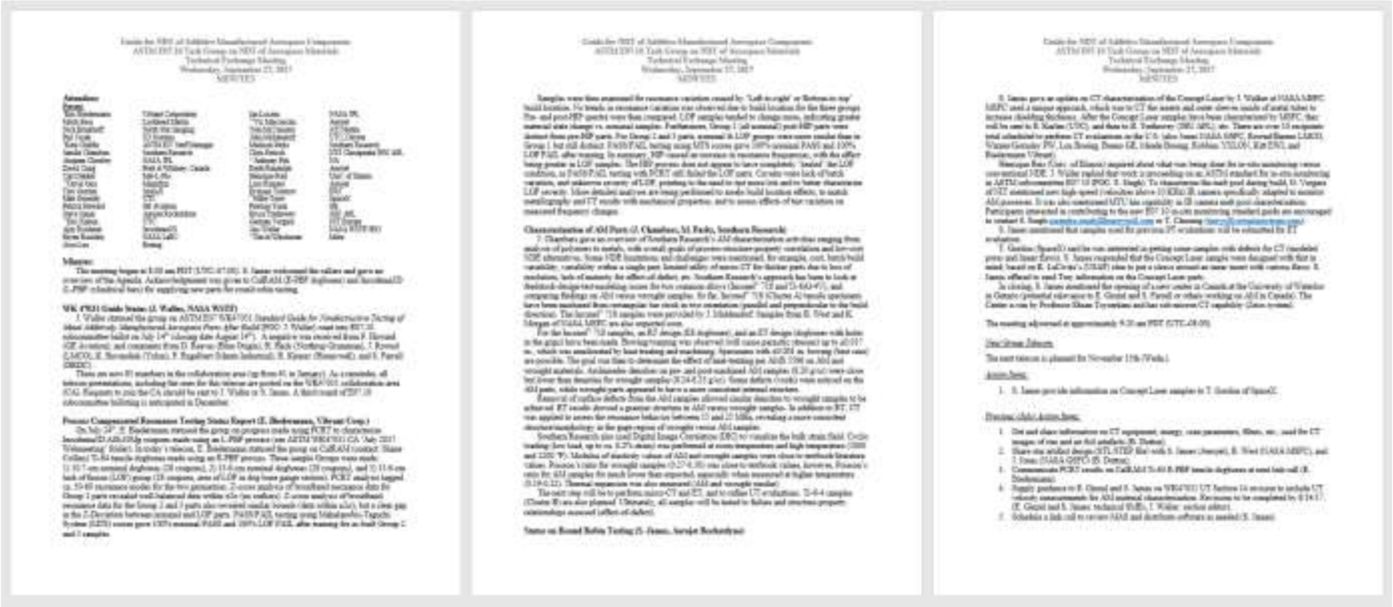
Two Week loan period
Present findings at WK47031 Link Call
Provide presentation to WK47031
Ship to next participant on list

Proposed Schedule

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

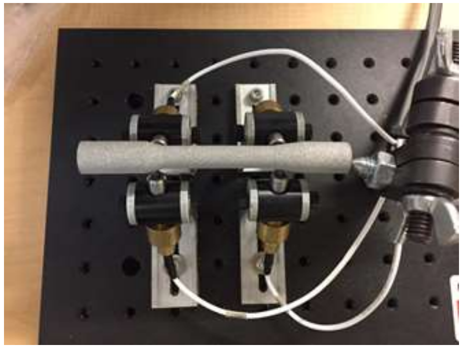
List with addresses will accompany the samples

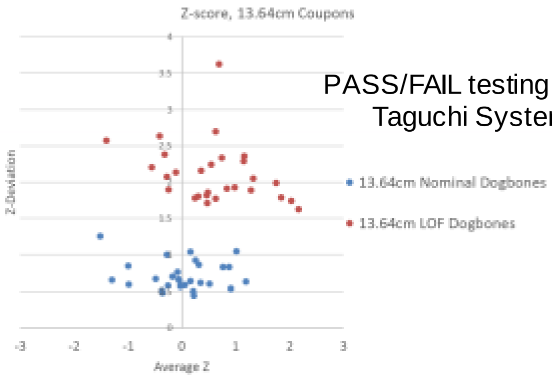
ASTM WK47031 Round Robin Activities / Sept. 27, 2017 telecon



September Webmeeting Round Robin Sample Activity

Vibrant statused the group on PCRT evaluation of three groups of CalRAM Ti6-4 tensile dogbones made using an E-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 gauge section).



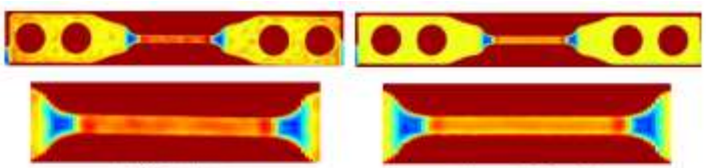


PASS/FAIL testing using Mahalanobis-Taguchi System (MTS) scores

September 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).

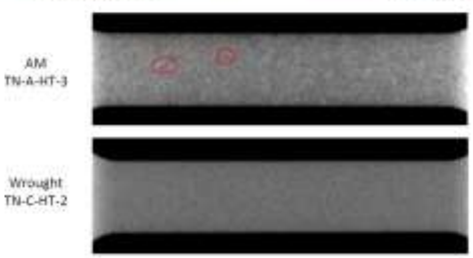
UT

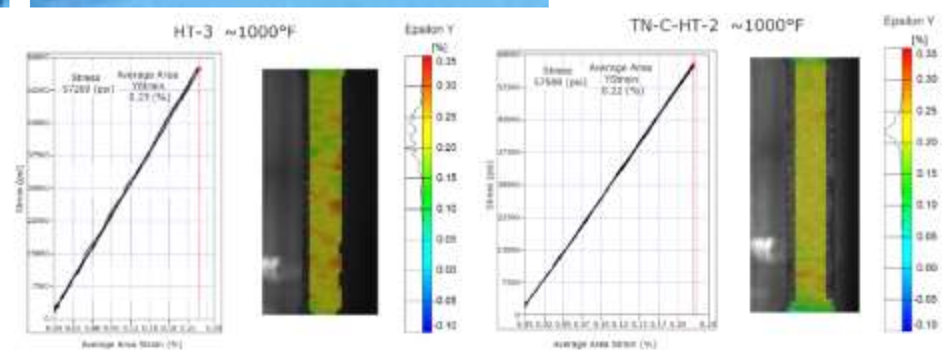


AM C-Scan Map

Wrought C-Scan Map

RT





AM Strain Field Visualization Max Load (500#)

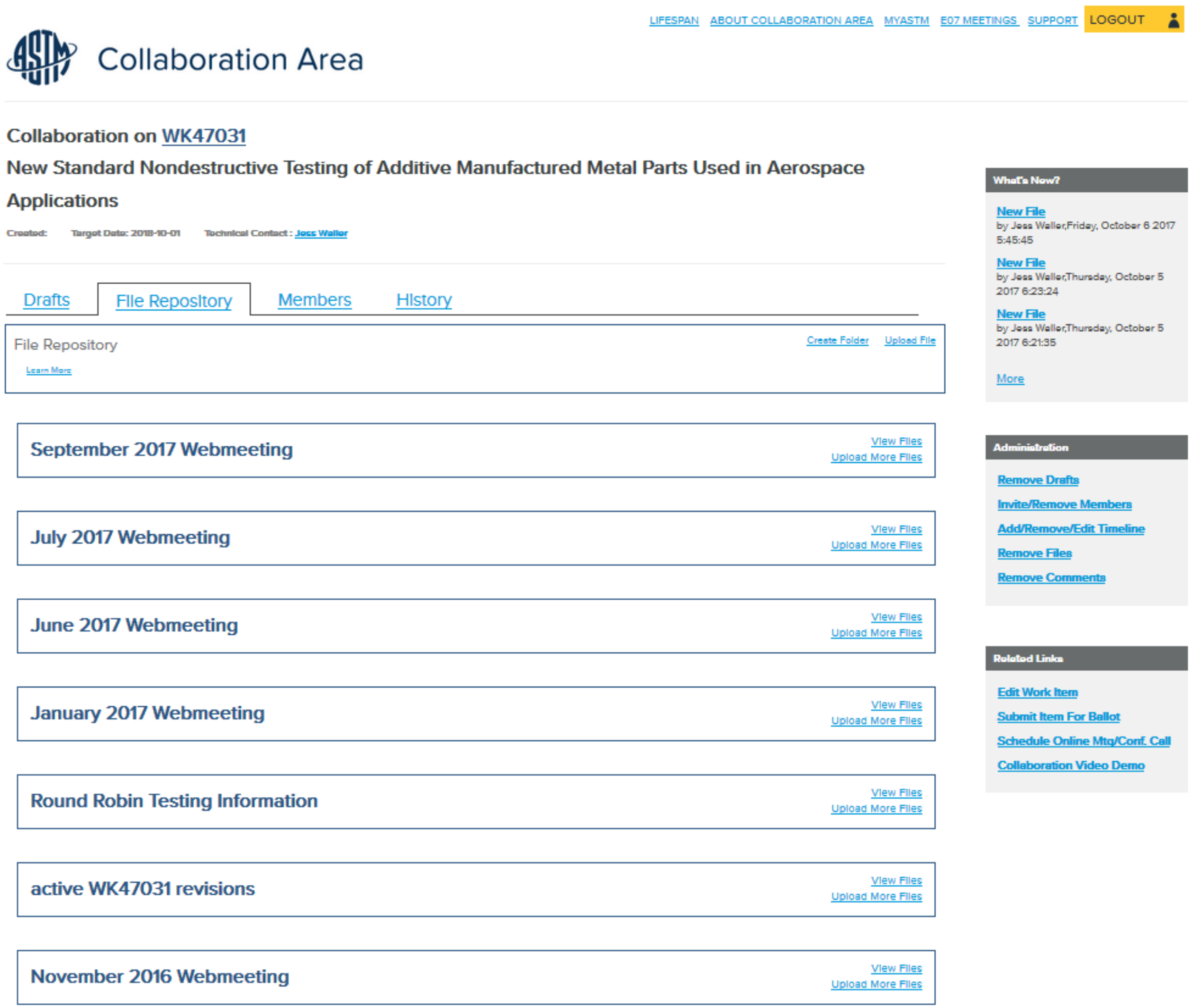
Wrought Strain Field Visualization Max Load (500#)

high temp DIC

- The next telecon will be November 15, 2017 at 11:00 a.m. EST

ASTM E07.10 WK47031 Round Robin Testing Online Collaboration Area

Working drafts of the Standard Guide, meeting minutes, and round-robin testing activity presentations are posted on-line:



Qualification & Certification

MEASUREMENT SYSTEM IDENTIFICATION METRIC/SI (ENGLISH) UNITS

National Aeronautics and Space Administration

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

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Marshall Space Flight Center, Alabama 35812

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MSFC TECHNICAL STANDARD

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

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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*

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)

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.

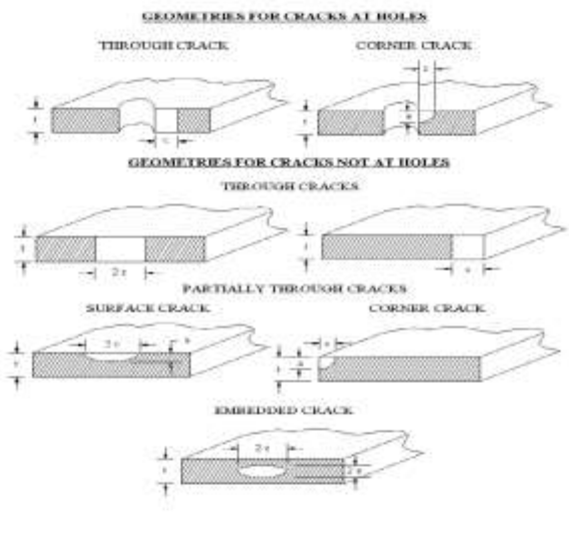

Figure 1—Assumed Flaw Geometries

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

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

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MSFC TECHNICAL STANDARD

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

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MSFC-SPEC-3717


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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

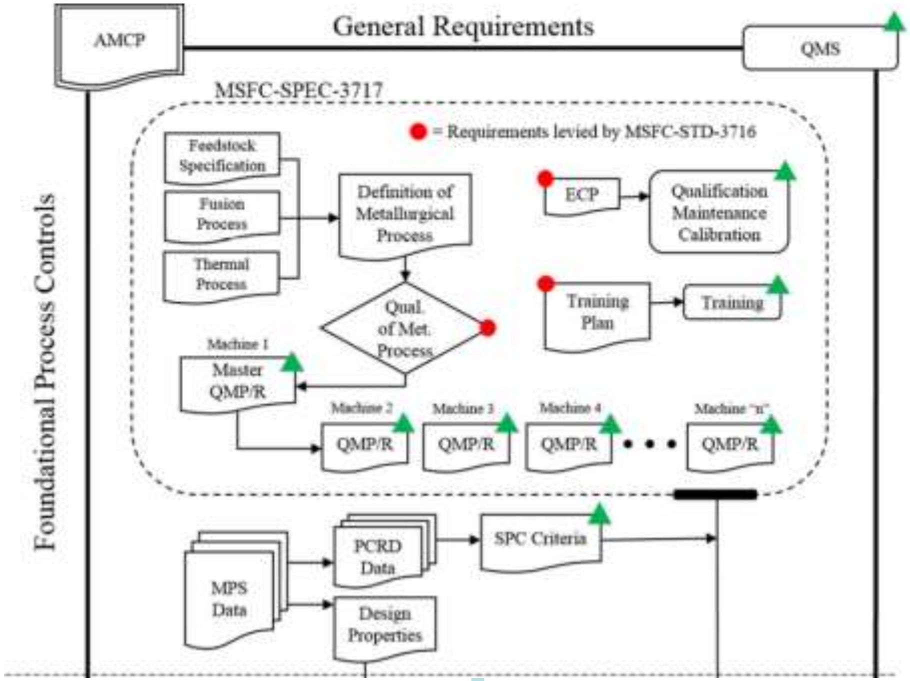
Lists process and part production control **requirements**:

- Qualified Metallurgical Process
- Equipment Control
- Personnel Training
- Material Property Design Values
- Part Design and Production Control Requirements

Contains **procedures** for implementing the requirements in 3616:

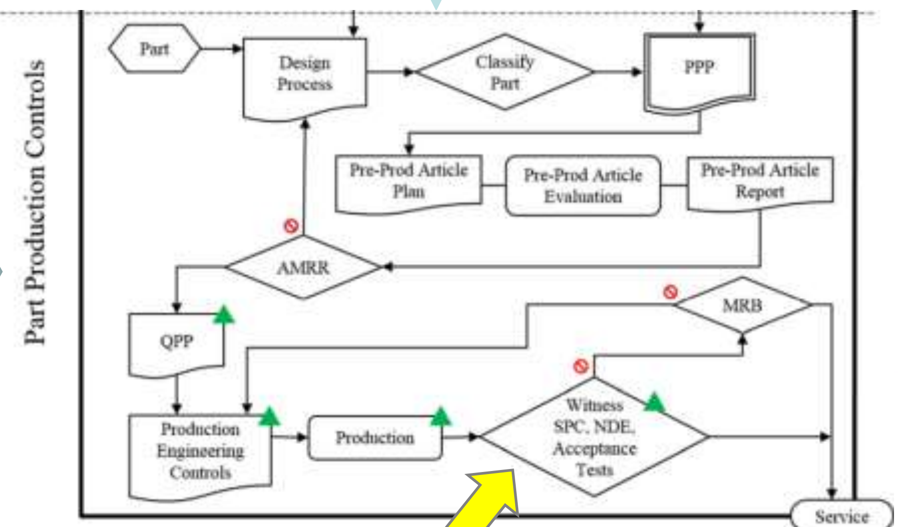
- Qualified Metallurgical Process
- Equipment Control
- Personnel Training

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



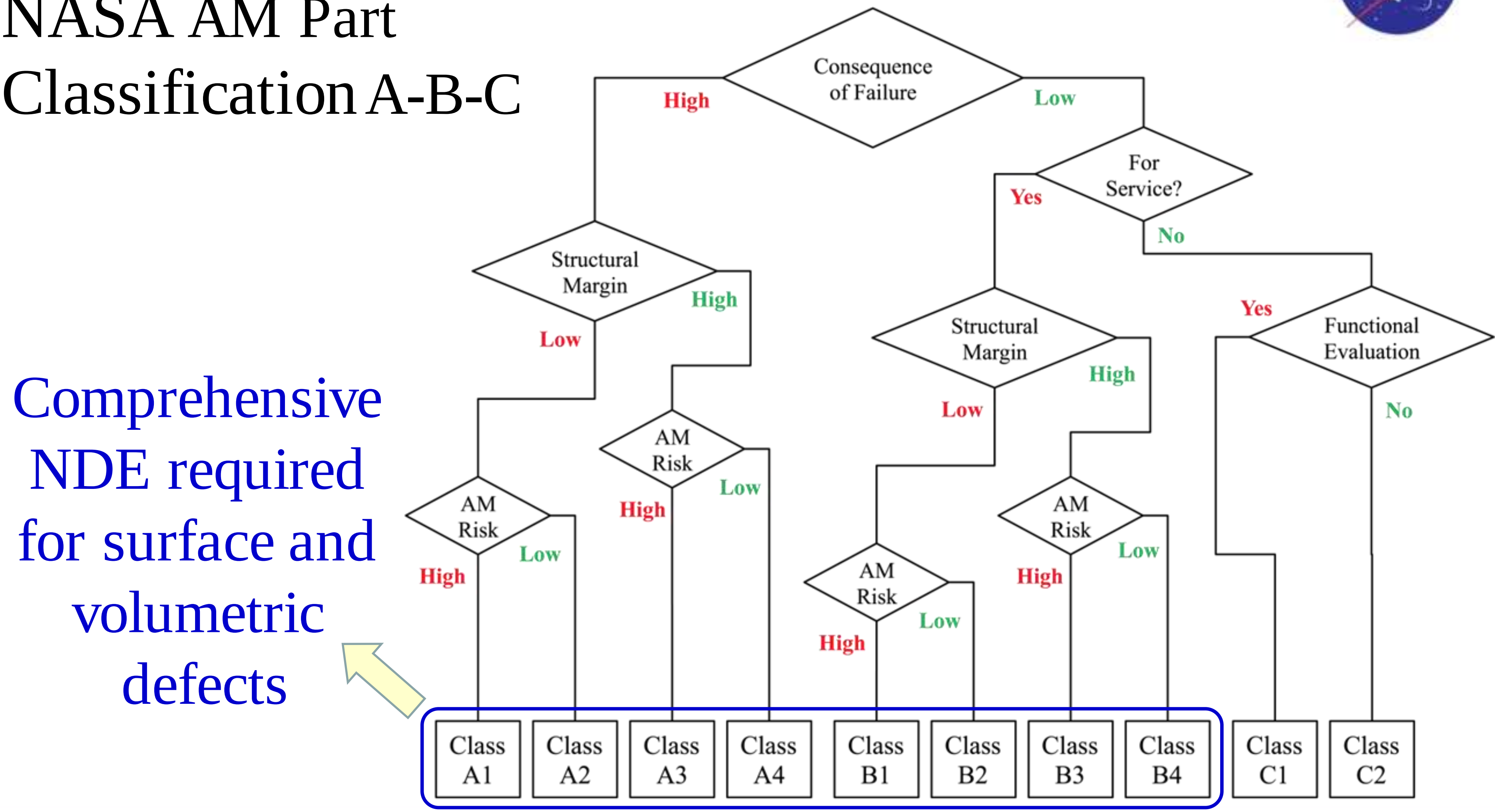
NDE decisional point

▲ 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

NASA AM Part Classification A-B-C



§ 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.

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*ABS plastic parts, MSFC/N. Werkheiser, T. Prater
CT, GSFC/J. Jones
*EBF[3] 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

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PT, Met-L-Check/M. White
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Commercial/Gov NDE

*Concept Laser/M. Ebert
*DRDC/S. Farrell
†*Airbus/A. Glover
*Incodema3D/A. Krishnan, S. Volk
†*CalRAM/S. Collins
†*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

Any Questions?

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

Synergy

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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