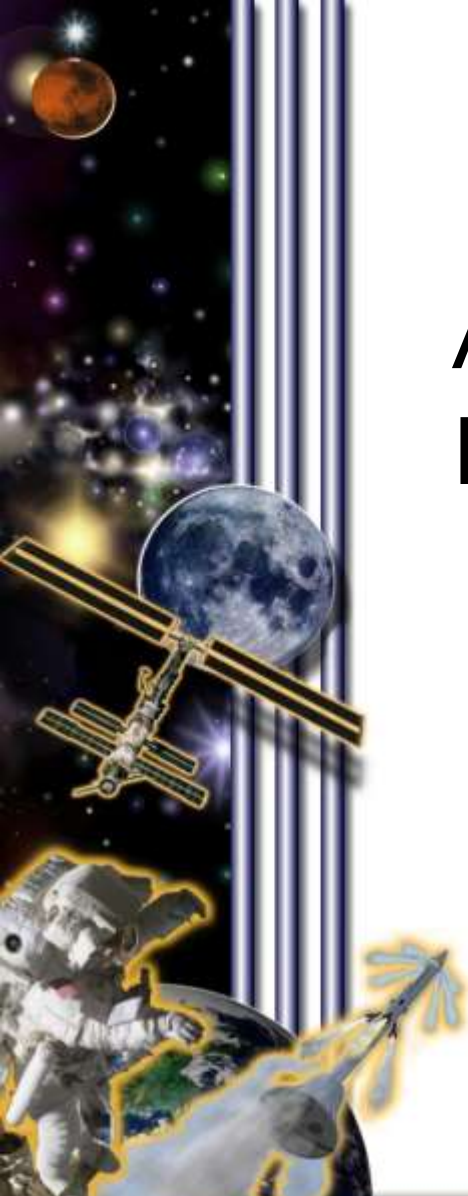


Additive Manufactured Product Integrity

Jess Waller ♦ NASA WSTF
Doug Wells ♦ NASA MSFC
Steve James ♦ Aerojet Rocketdyne
Charles Nichols ♦ NASA WSTF

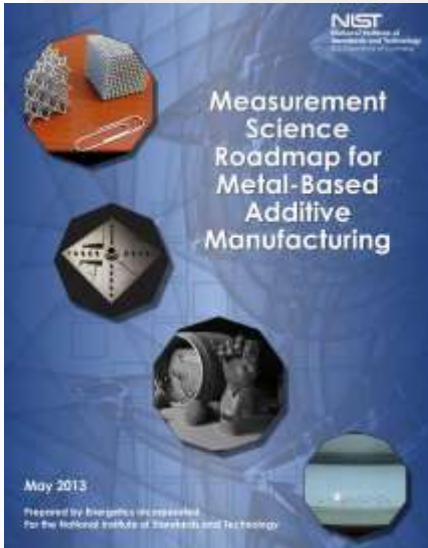
Quality Leadership Forum
March 15 & 16, 2017
Cape Canaveral, FL

1:30 - 2:00 PM, Wednesday, March 15, 2017

Background

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

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




NASA/TM—2014-218560

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

November 2014

NASA
Additive Manufacturing
Roadmap and NDE-related
Technology Gaps


AFRL-RX-WP-TR-2014-0162

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

EWI

JUNE 2014
Interim Report

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


EM20

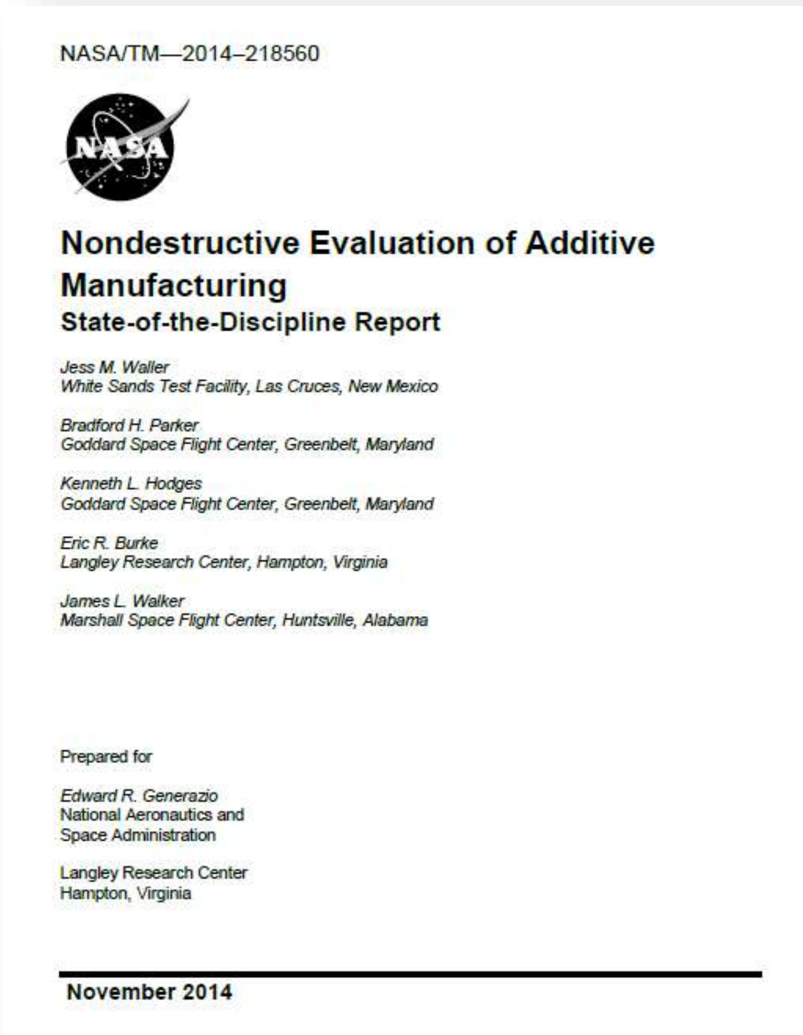
MSFC TECHNICAL STANDARD

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

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

Background


NASA/TM—2014–218560

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

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

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

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

Eric R. Burke
Langley Research Center, Hampton, Virginia

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

Prepared for

Edward R. Generazio
National Aeronautics and
Space Administration

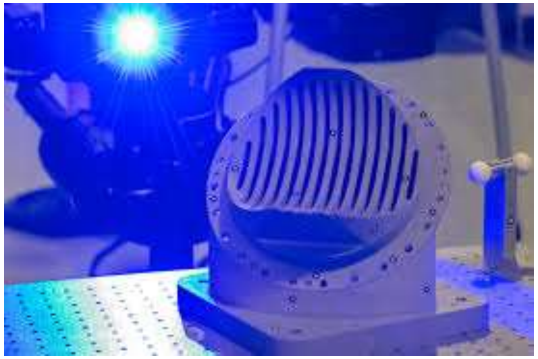
Langley Research Center
Hampton, Virginia

November 2014

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

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

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

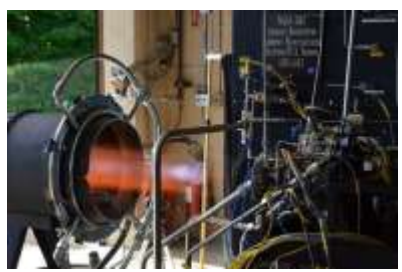
EBF^3 wire-fed system during parabolic fight testing

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

Additive Manufacturing Technology Gap Analysis

NDE of AM Technology Gaps

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

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

NDE Discussion Points

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

NDE of As-Built and Post-Processed AM Hardware

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

NNWG

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

Identify Relevant AM Defects

NDE of AM Technology Gaps

- Develop/generate an AM 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
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Background

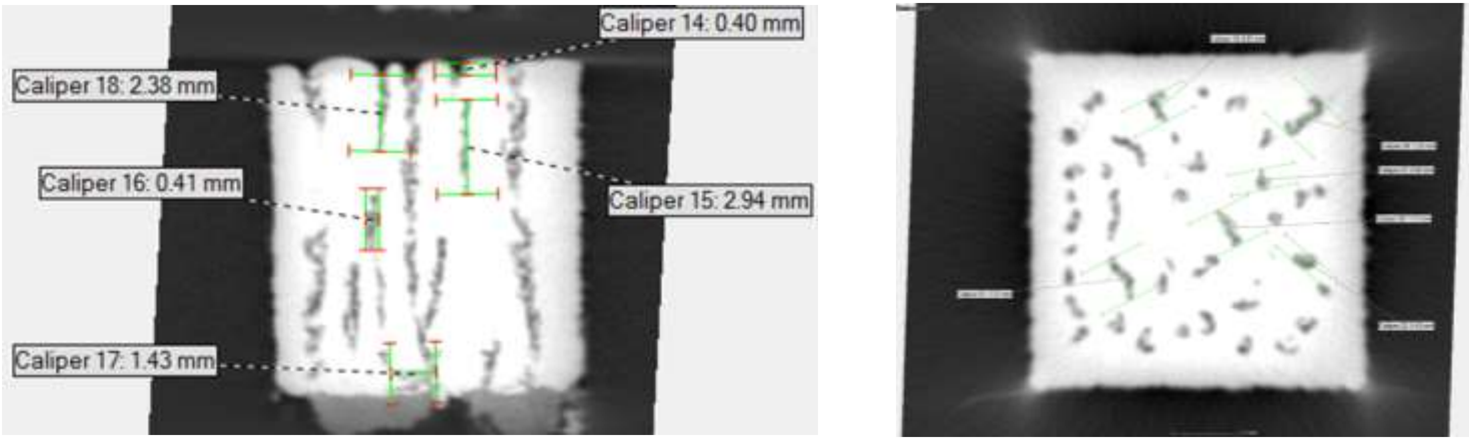
While certain AM flaws (e.g., voids and porosity) can be characterized using existing standards for welded or cast parts, other AM flaws (layer, cross layer, unconsolidated and trapped powder) are unique to AM and new NDE methods are needed.

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

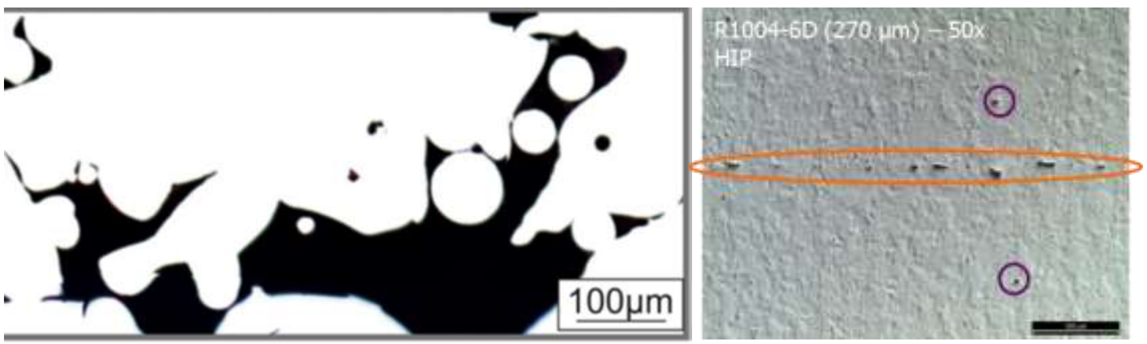
Develop new NDE methods

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

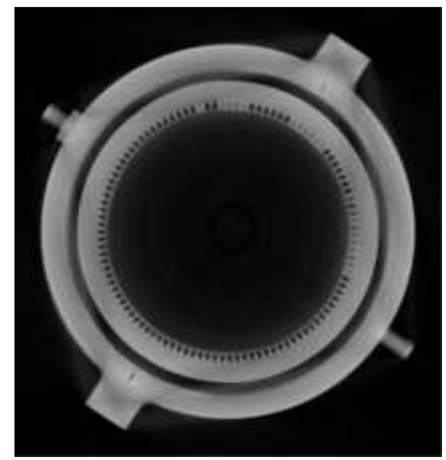
Note: DED = Directed Energy Deposition., PBF = Powder Bed Fusion



Cross layer



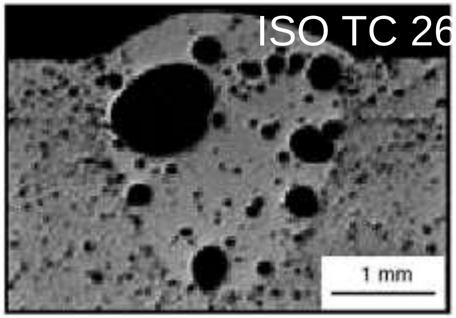
Layer

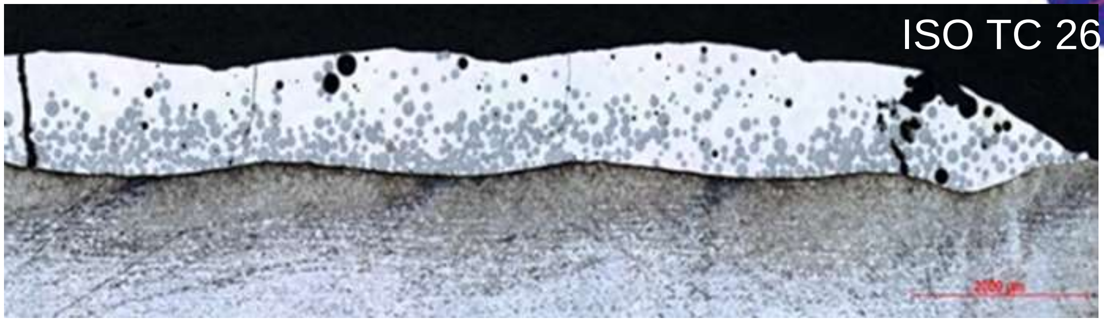


Trapped Powder

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

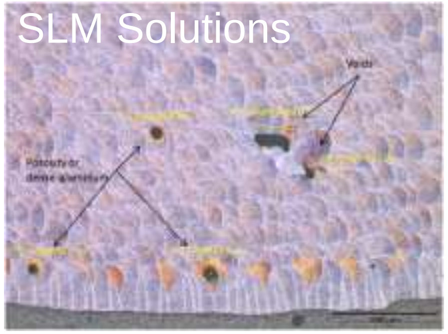
Typical PBF and DED Defects

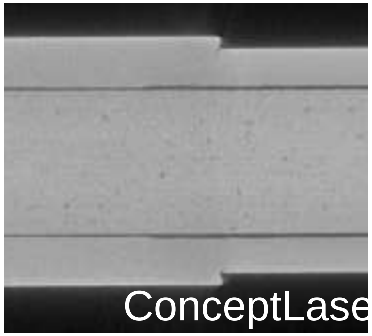


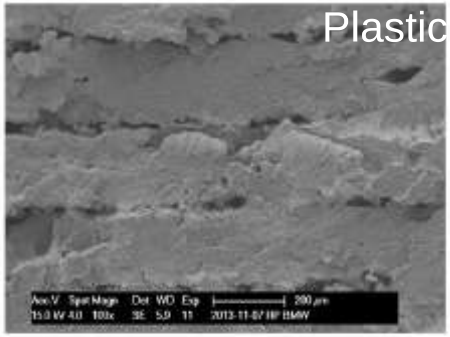


PBF Porosity

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 NDT methods, while porosity inside the part reduces strength in its vicinity. Like voids, gas porosity causes a part to be less than fully dense.

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

Develop and Capture Best NDE Practice

Round Robin Test Goals

- 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
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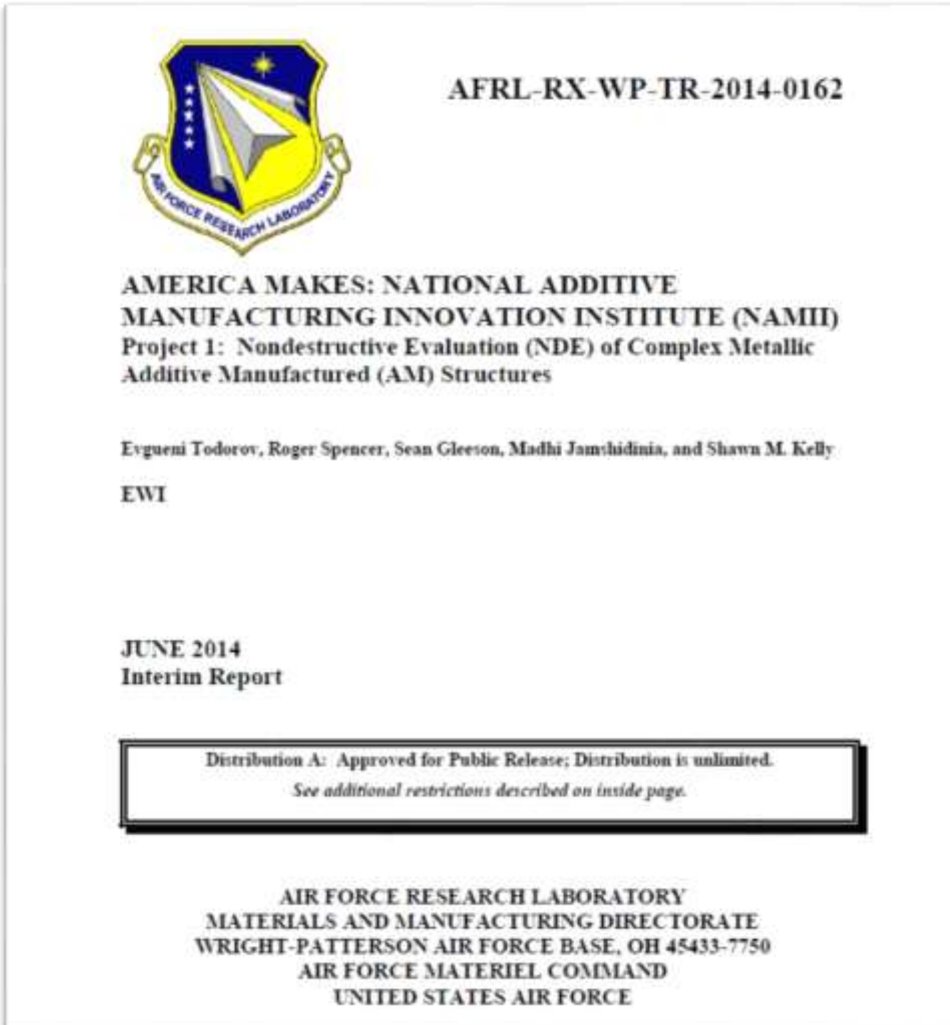
Effect of Design Complexity on NDE



AFRL-RX-WP-TR-2014-0162

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

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

EWI

JUNE 2014
Interim Report

Distribution A: Approved for Public Release; Distribution is unlimited.
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)*

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

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.

Background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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:

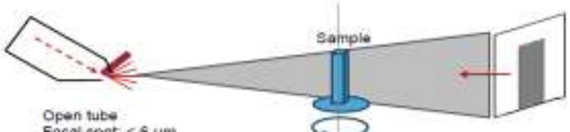
(a) Only surfaces providing good access for application and cleaning
(b) Areas where shadowing of acoustic beam is not an issue
(c) External surfaces and internal surfaces where access through conduits or guides can be provided
(d) Areas where large number of exposures/shots are not required

§ 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.

µCT Requirements

CT System

NorthStar X50



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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 NASA capability at GRC, KSC and GSFC

Process Compensated Resonance Testing

Vibrant

Process Compensated Resonance Testing (PCRT) for Additive Manufacturing

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

Vibrant

Standards and Approvals for PCRT

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

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

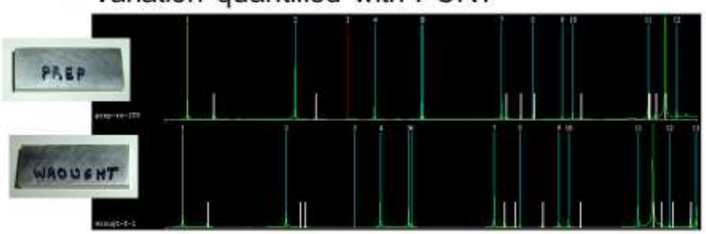
Federal Aviation Administration Approved – Since July of 2010 for the detection of micro-structural changes indicating over-temp of turbine blades (JT8D-219 HPT)

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

Vibrant

Titanium Samples

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



12

Vibrant

AM Process Variation

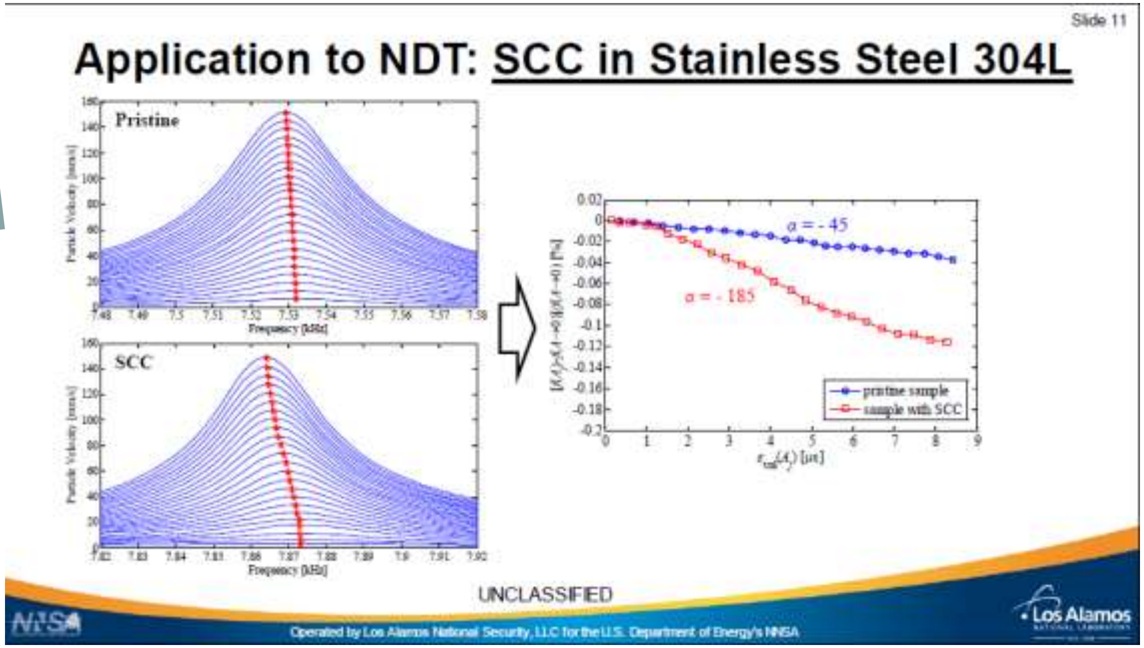
- Sensitivity to thermal process variation
  - FAA-approved JT8D overtemp at Delta
  - Works for additive manufacturing processes

11

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

Nonlinear Resonant Ultrasonic Testing (RUS)

TRL4 system available with advanced software



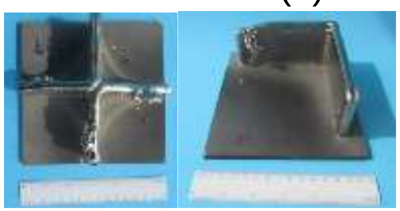
- Frequency scan at more than more amplitude
- Shows promise for detection of initial defects before catastrophic failure
- Signal not affected by part size or geometry
- MSFC to supply samples to LANL

Coordinated by S. James (Aerojet Rocketdyne)

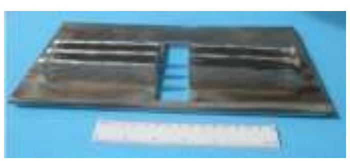
Electron Beam Freeform Fabrication (EBF^3)

NASA LaRC
Inconel 625 on copper

Ti-6Al-4V (4)



SS 316



Al 2216

Laser-PBF (L-PBF)

Gong
Ti-6Al-4V bars

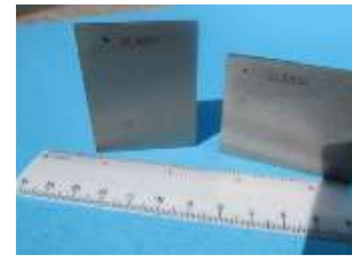
Airbus
Al-Si-10Mg dog bones

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

Concept Laser Inconel 718 prisms for CT capability demonstration

Electron Beam-PBF (E-PBF)

Met-L-Check
SS 316 PT/RT panels



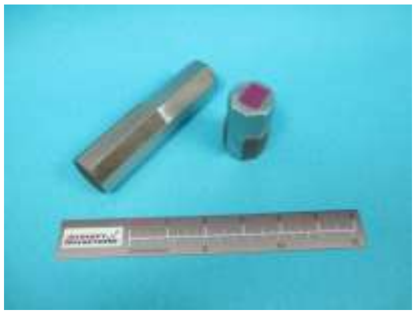
Characterized to date by various NDE techniques (CT, RT, PT, PCRT, UT)

ASTM WK47031 Round Robin Testing (Leveraged)

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

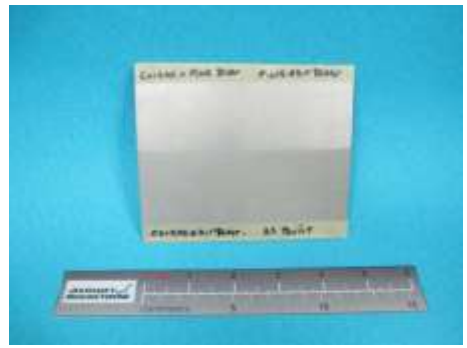
HEX Samples

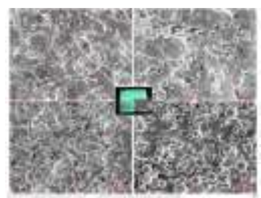
Inconel 718
in two different build orientations



SLM (L-PBF)

Inconel 625 PT sheets





Laser-PBF (L-PBF)

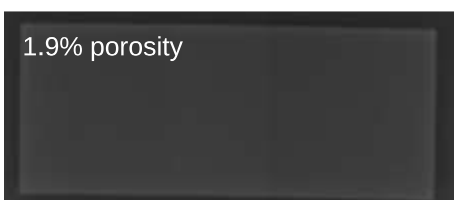
NASA MSFC nominal and off-nominal metal parts (K. Morgan)

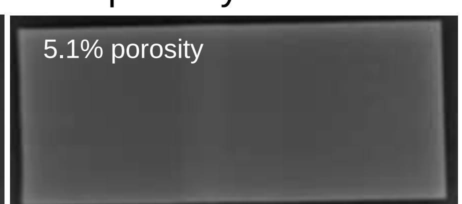
Directed Energy Deposition (DED)

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

DRDC Porosity Standards

4140 steel. 0-10% porosity





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

Round Robin Sample Activity – illustrative presentations

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

Collaboration Area

Collaboration on WK47031

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

- November 2016 Webmeeting
- June 2016 Webmeeting
- May 2016 Webmeeting
- February 2016 Webmeeting
- January 2016 Webmeeting
- December 2015 Webmeeting
- October 2015 Webmeeting
- September 2015 Webmeeting
- August 2015 Webmeeting
- Round Robin Testing Information
- May 2015 Webmeeting
- July 2015 Webmeeting

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

NASA

POD/fracture critical AM parts, ESA/Gerben Sinnema
AE, MRI/Ed Ginzel
CT/acoustic microscopy, Honeywell/Surendra Singh
UT/PT, Aerospace Rocketdyne/Steve James
CT/RT, USAF/John Brausch, Ken LaCivita
CT, Fraunhofer/Christian Kretzer
CT, GE Sensing GmbH/Thomas Mayer
PCRT, Vibrant Corporation/Eric Biedermann
PT, Met-L-Check/Mike White
Nonlinear RUS, LANL/Marcel Remillieux

Commercial/Gov NDE

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

Commercial/Gov AM Round Robin Sample Suppliers

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

Voluntary Consensus Standards Gap Analysis

NDE of AM Technology Gaps

- Develop/generate an AM defects catalogue
- Develop in-process NDE to improve feedback control, maximize part quality and consistency, and obtain ready-for-use certified parts
- Develop post-process NDE of finished parts
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ASTM Subcommittee E07.10 on Specialized NDT Methods

Designation: X XXXX-XX

Work Item Number: 47031
Date: November 17, 2016

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

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

In Ballot!

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

WK47031 Collaboration Area Membership

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

Learn More

65 current members

NASA, JAXA, ESA, NIST, USAF, GE Aviation, Aerojet Rocketdyne, Lockheed, Honeywell, Boeing, Aerospace Corp, ULA, academia and various AM and NDE community participants are represented

(48 current members as of June ASTM E07 Committee on NDT meeting)

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

America Makes & ANSI AMSC Findings

- 181 members (early June)
- Walker, Wells, Luna and Waller among NASA-affiliated members on roster
- Industry Review of Roadmap - December 14, 2016
- Comments being reviewed now by appropriate WGs
- The roadmap will be published by the end of February 2017
- 89 standards gaps identified
  - 6 nondestructive evaluation gaps
  - 15 qualification and certification gaps
  - 6 precursor materials gaps
  - 17 process control gaps
  - 5 post-processing gaps
  - 5 finished materials gaps
  - 26 design gaps
  - 8 maintenance gaps
- Future meetings of Standards Development Organizations will discuss how the standards are divvied up

America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)

America Makes
National Additive Manufacturing Innovation Institute

ANSI
American National Standards Institute

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

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

Meets: Every other Friday 11 am – 12:30 pm Eastern, beginning May 27, 2016
Co-chairs: Patrick Howard, General Electric, and Steve James, Aerojet Rocketdyne

Scope: NDE of Finished Parts
(NDE for process monitoring under Process Control SG of Process and Materials WG)
Test methods or best practice guides for NDE of AM parts
Dimensional metrology of internal features
Geometry and surface texture measurement techniques (especially for internal features)
Data fusion of above
Common defects catalog found in AM parts, and process capability assessments of NDE techniques (e.g. PBF vs. DED defects)
Terminology (e.g., definition of AM defects)
Intentionally seeding AM flaws
Test samples for process capability or NDE technique performance evaluation

<u>Qualification & Certification (Q&C) WG</u>

Meets: Every other Monday, 2:30 – 4 pm Eastern, beginning May 9, 2016
Co-chairs: Capt. Armen Kurdian, U.S. Navy, and Shawn Moylan, NIST

Ensure that all stages of a particular AM process have a set of commonly understood standards to enable Qualification (Qualification is defined as ensuring suitability to meet functional requirements in a repeatable manner)
Ensure that AMSC WGs have adequate representation from industry & government
Generate checklists to address all aspects of AM, to cover variability, repeatability, suitability, etc
Address all aspects of the AM environment (materials, design, personnel, systems, end product, etc.)
Identify aspects of AM process which would lend themselves to certification

ASME ISO ASTM INTERNATIONAL SAE AWS

America Makes & ANSI AMSC Working Groups

America Makes
National Additive Manufacturing Innovation Institute

ANSI
American National Standards Institute

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

Process and Materials WG*

Meets: Every 4^{th} 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

ASME ISO ASTM INTERNATIONAL SAE AWS

America Makes & ANSI AMSC Working Groups

America Makes
National Additive Manufacturing Innovation Institute

ANSI
American National Standards Institute

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

Design WG
Meets: Every other Tuesday, 10-11:30 am Eastern, beginning May 10, 2016
Co-chairs: John Schmelzle, NAVAIR, and Jayanthi Parthasarathy, MedCAD

Input (Design guides, Design intent)
Designing parts (Design tools, Simulation and modeling, Design for assemblies, Design for printed electronics, Design for bio)
Design documentation (Neutral build file, Product definition data sets)
Validation (of design and models)

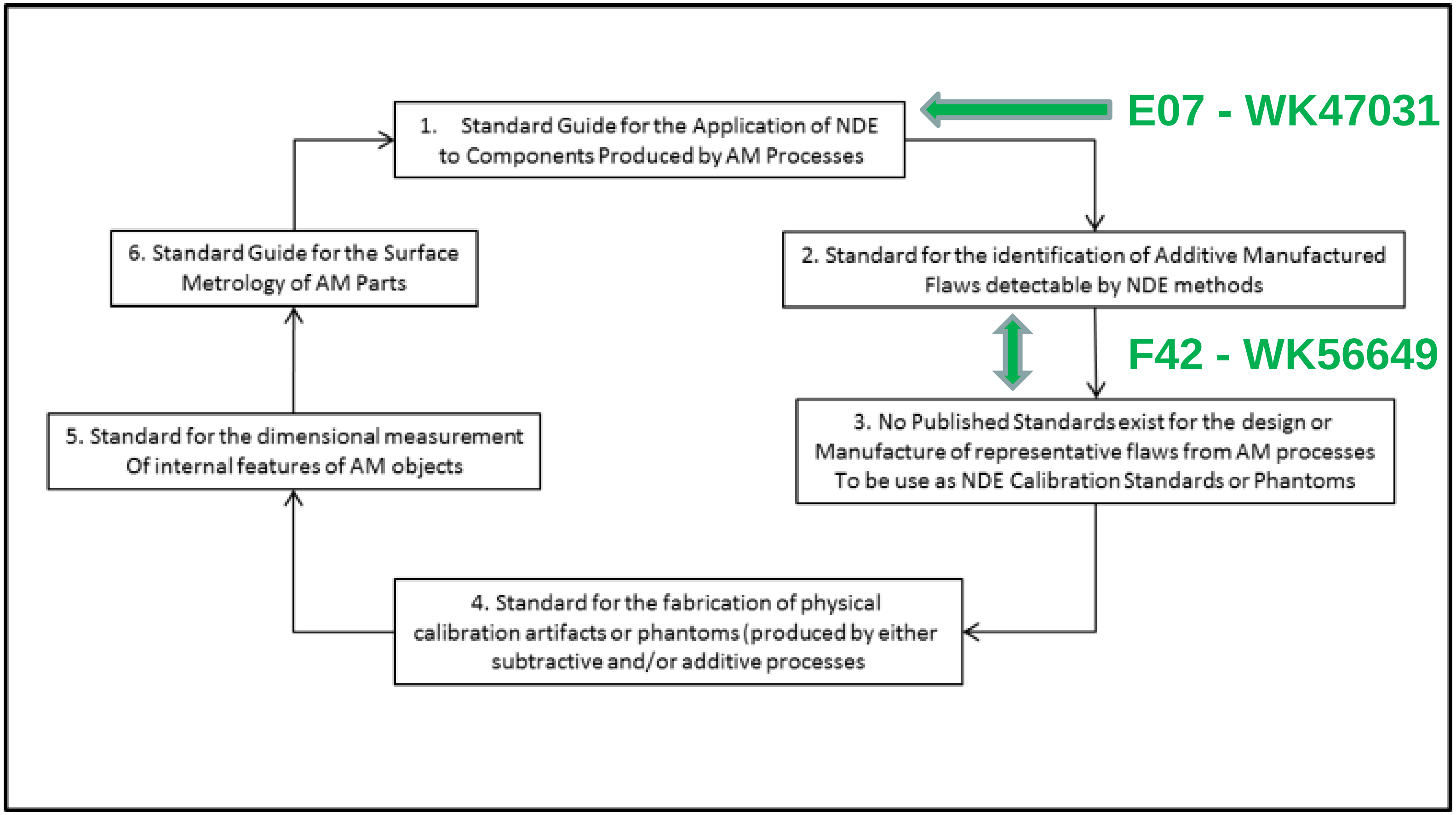
Maintenance WG
Meets: Every other Monday 2-3:30 pm Eastern, beginning May 16, 2016
Co-chairs: David Coyle, NAVSUP WSS, and Michele Hanna, Lockheed Martin

Scope: Maintenance of parts and machines
Standard repair procedures for parts and tooling
Standard inspection processes
Model based inspection
Standards for tracking maintenance operations
Workforce development
Cybersecurity

ASME ISO ASTM INTERNATIONAL SAE AWS

Gaps Identified by NDE Working Group

Standards in progress



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

Draft: WK47031 POC: J. Waller

E07

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

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

Draft: WK56649 POC: S. James

F42

Standard Guide for
Intentionally Seeding Flaws in Additively Manufactured Parts

Draft in Preparation

Draft: WKXXXX POC: S. Singh

E07

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

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

Draft: WKXXXX POC: TBD

E07

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

Future

Draft: WKXXXX POC: TBD

E07?

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

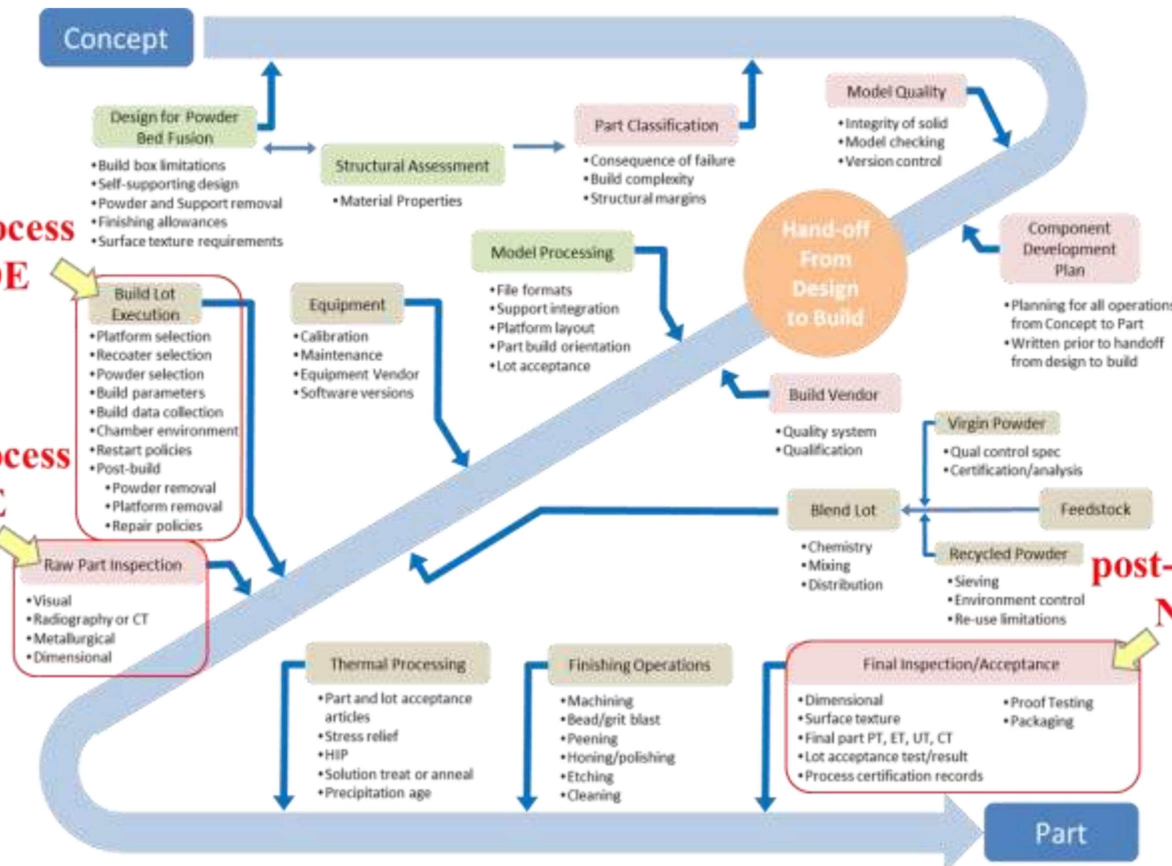
Future, phys ref stds to demonstrate NDE capability

Future Standards for NDT of AM Aerospace Materials

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

Singh: new E07 standard → **in-process NDE**

Waller: WK47031 → **post-process NDE**



post-process NDT ← Waller: WK47031

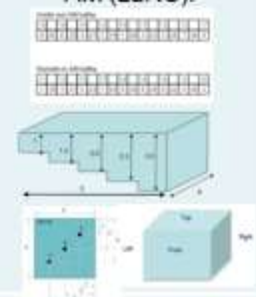
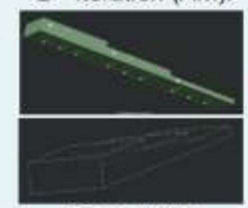
- 1/23/17: E07.10 motion to register a new standard and assign jurisdiction passed

Demonstrate NDE Capability

NDE of AM Technology Gaps

- Develop/generate an AM defects catalogue (NEW)
- Develop in-process NDE to improve feedback control, maximize part quality and consistency, and obtain ready-for-use certified parts
- Develop post-process NDE of finished parts
- Develop voluntary consensus standards for NDE of AM parts
- Develop better physics-based process models using and corroborated by NDE
- Use NDE to understand scatter in design allowables database generation activities (process-structure-property correlation)
- 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

	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): 	2^{nd} 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

Understand Effect-of-Defect

NDE of AM Technology Gaps

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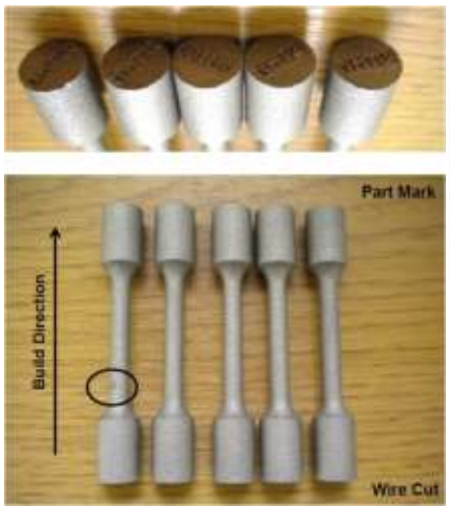
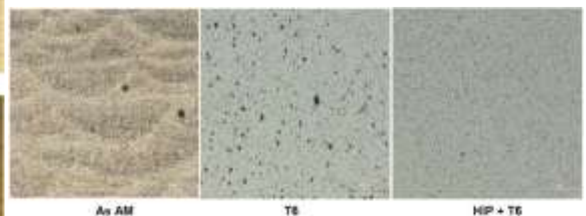
Approach

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

1. Airbus Laser PBF samples



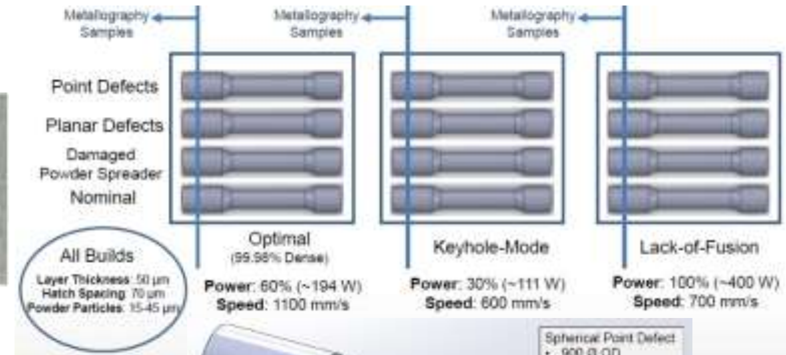
AlSi10Mg ASTM E8 compliant dogbones
13mmØ, 85mm long (6mmØ, 30mm Gauge Length)

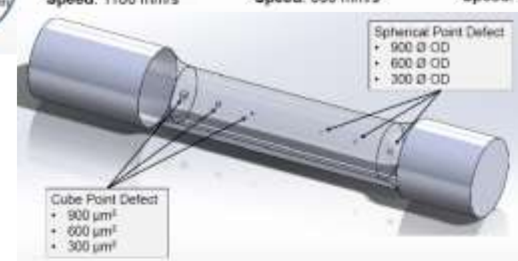


Investigate effect post-processing on microstructure and surface finish on fatigue properties

Airbus study on effect of process parameters on final properties

2. UTC Laser PBF samples





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

CT at GRC as of November

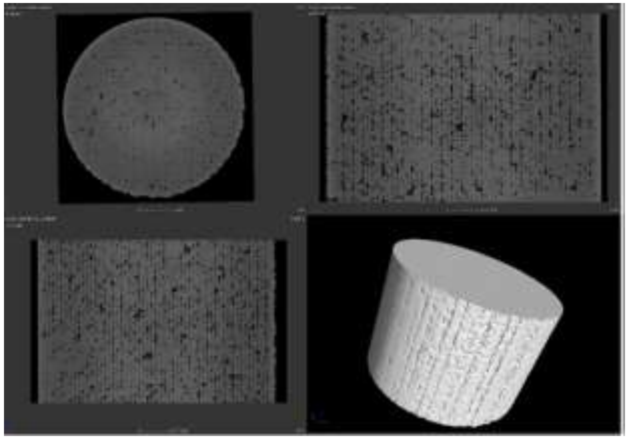
Other NDE planned in ASTM NDT Taskgroup

Parallel effort

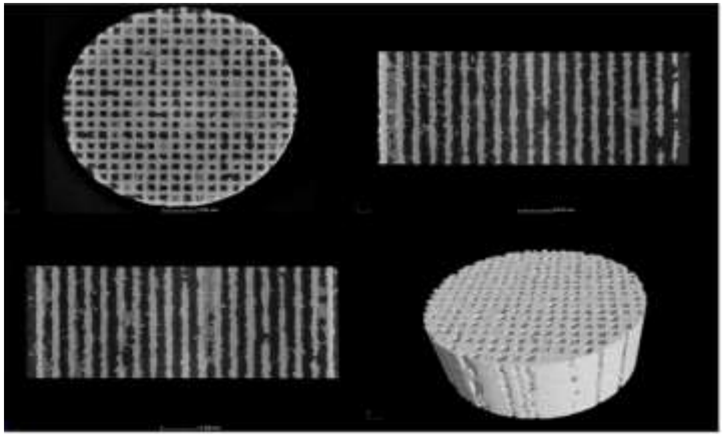
Determine effect-of-defect on sacrificial specimens w/ seeded flaws

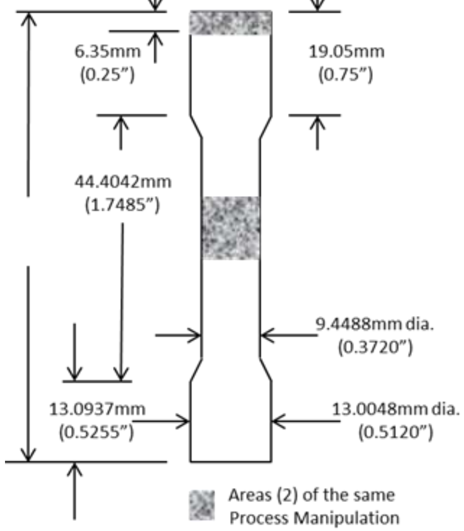
America Makes Ed Morris (VP) call to fabricate samples for NDE in support of ASTM WK47031 effort

Insert 1 "Lower Laser Power"

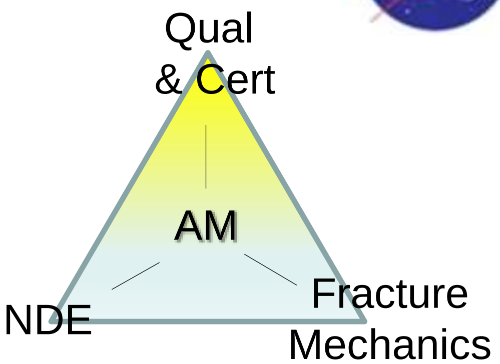


Insert 4 "Trace Width Bigger"





3. CalRAM Electron Beam PBF samples



December 18, 2016

TO: Members of Committees E08, E07 and F42

SAVE THE DATE

Round Table Discussion: Mechanical Behavior of Additive Manufactured Components
May 5, 2016
San Antonio, TX

About the Event

A Round Table Discussion on Mechanical Behavior of Additive Manufactured Components will be held Thursday, May 5, 2016 and is sponsored by ASTM Committee E08 on Fatigue and Fracture in conjunction with F42 on Additive Manufacturing Technologies and E07 on Nondestructive. The discussion will be held at the Grand Hyatt San Antonio in San Antonio, TX, in conjunction with the May standards development meetings of the committee.

The Round Table Discussion is a supplement to the Workshop on Mechanical Behavior of Additive Components and will provide a forum for the exchange of ideas regarding the mechanical behavior of components fabricated using additive manufacturing, with a focus on the development of fatigue related standards for additive manufacturing.

For more information please visit: http://www.astm.org/E08RTD5-2016

If you have any questions, please contact me by reply.

Hannah Sparks
Administrative Assistant, Symposia Operations

ASTM INTERNATIONAL
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Address:

- Fracture & fatigue of AM parts
- AM parts used in fracture critical applications
- Critical flaw size for AM defects

Qualify & Certify AM Spaceflight Hardware

NDE of AM Technology Gaps

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

National Aeronautics and Space Administration

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

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

EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

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

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

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

Contact: *Doug Wells (MSFC)*

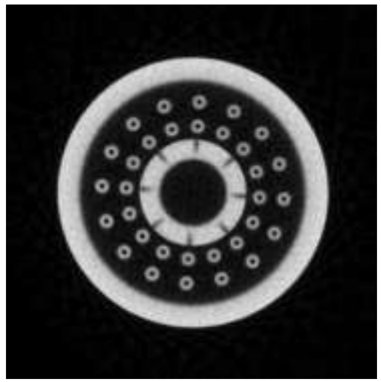
- Comprehensive draft technical standard is in review
- All Class A and B parts are expected to receive comprehensive NDE for surface and volumetric defects within the limitations of technique and part geometry
- Not clear that defect sizes from NASA-STD-5009[§] are applicable to AM hardware
- NDE procedural details are still emerging
- Target release: Dec. 2016

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

Aspects of MSFC AM Process Control

Draft NASA MSFC Standard implements four fundamental aspects of process control for AM:

Metallurgical Process Control



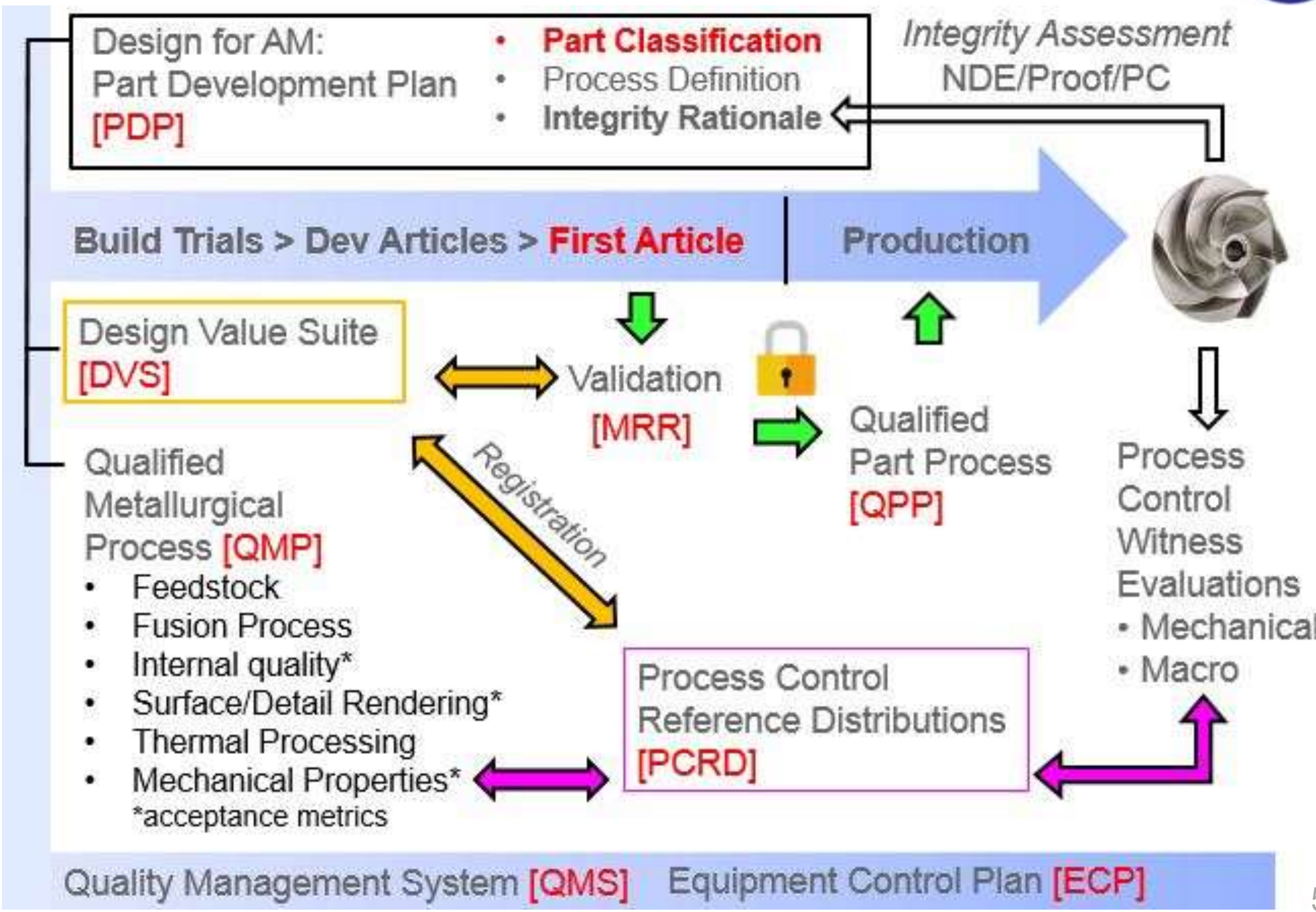
Part Process Control

Equipment Process Control

Build Vendor Process Control

- 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 standard provides a consistent framework for these controls and provides a consistent set of review/audit products

Overview of MSFC AM Standard



Products of the MSFC AM Standard

PDP = Part Development Plans (Overview and implementation)

- Communication, convey risk
- Classification and rationale

DVS = Design Value Suite (properties database)

- "Allowables," integrated through PCRDs

QMP = Qualified Metallurgical Process (foundational control)

- Analogous to a very detailed weld PQR

PCRD = Process Control Reference Distribution

- Defined reference state to judge process consistency

FAI = First Article Inspection

MRR = Manufacturing Readiness Review

QPP = Qualified Part Process

- Finalized "frozen" part process

ECP = Equipment Control Plans

- Machine qual, re-qual, maintenance, contamination control

QMS = Quality Management System

- Required at AS9100 level with associated audits

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, HCF, LCF, fracture}
3. AM Risk (High/Low) {Integrity evaluation, build complexity, inspection access}

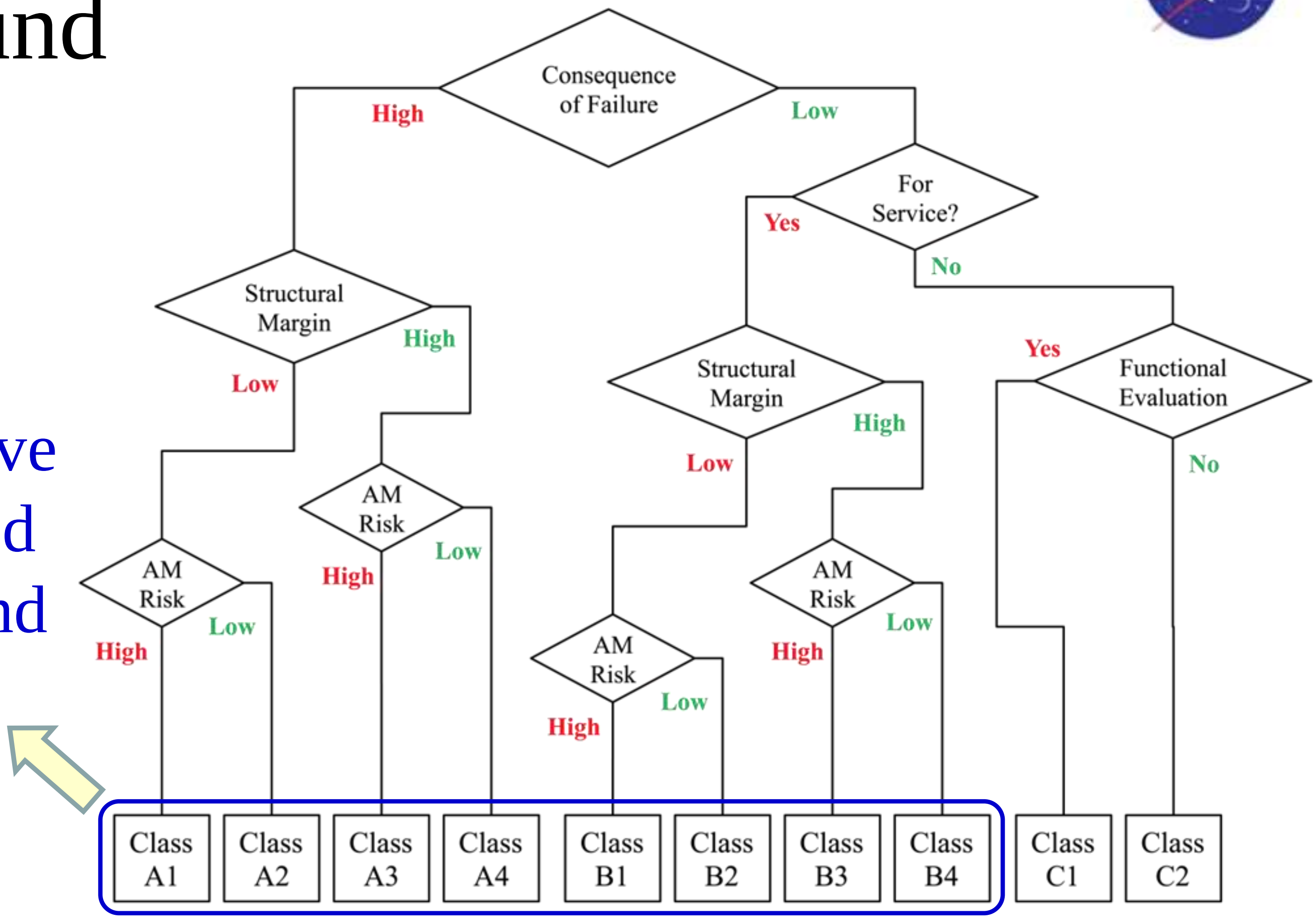
Part classification is highly informative to part risk, fracture control evaluations, and integrity rationale

Example:

A3 = fracture critical part with low structural demand (high margin) but challenges in inspection, geometry, or build

Background

Comprehensive NDE required for surface and volumetric defects



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

THIS IS ONLY THE BEGINNING

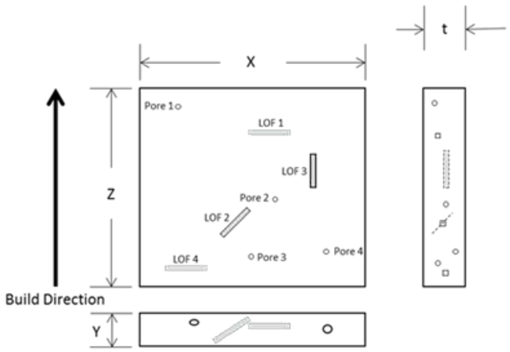
Back-ups

Gaps Identified by AMSC NDE Working Group:

- Led by Patrick Howard, GE Aviation
- 28 members drawn from aerospace, automotive and medical industries
- Mapping started May 2016 – September2016
  - One Face-to-face meeting
- Met bi-weekly – Web meeting
  - Hosted by ANSI
  - 6 to 8 members participated
  - Identified 6 Standardization Gaps

Demonstrate NDE capability

RT & PCRT Sample

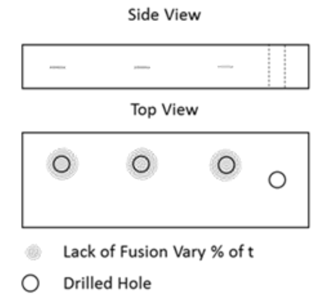


Artifact Lack of Fusion	Depth	Length	Orientation to build direction
LOF 1	1% of Thickness or 1 layer x ¼ t	.25" (6.35mm)	0°
LOF 2	2% of Thickness or 2 layers x ¼ t	.25" (6.35mm)	45°
LOF 3	3% of Thickness or 3 layers x ¼ t	.25" (6.35mm)	90°
LOF 4	4% of Thickness or 4 layers x ¼ t	.25" (6.35mm)	0°

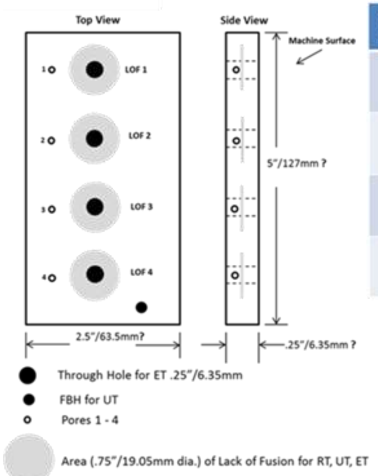
Artifact	Diameter
Pore 1	.5% of t
Pore 2	1% of t
Pore 3	1.5% of t
Pore 4	2% of t

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

ECT Sample



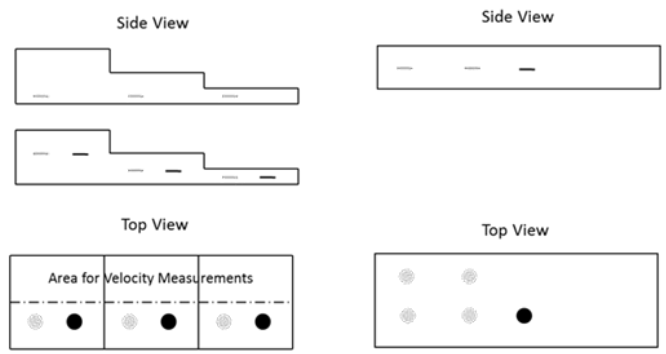
Multiuse Sample (MUS)



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°

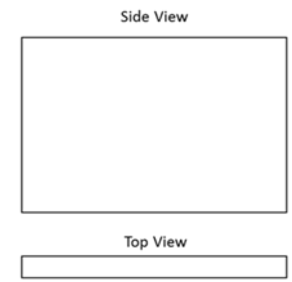
Artifact	Diameter
Pore 1	.5% of t
Pore 2	1% of t
Pore 3	1.5% of t
Pore 4	2% of t

UT Sample
Stepped vs. One Thickness



Lack of Fusion Vary % of t
Flat Bottom Hole

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).

Qualification & Certification/NASA MSFC AM Risk, Cumulative Criteria

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 $\geq$ 1mm in cross-section?	0	2	
Critical regions of the part **do not** require sacrificial supports?	0	2	
		Total	

- It is incumbent upon the structural assessment community to define critical initial flaw sizes (CIFS) for the AM part to define the objectives of the NDE.
- Knowledge of the CIFS for AM parts will allow the NDE and fracture control communities to evaluate risks and make recommendations regarding the acceptability of risk.
- CIFS defects shall be detected at the accepted probability of detection (POD), e.g., 90/95, for fracture critical applications.
- **Demonstration of adequate part life starting from NASA-STD-5009 flaw sizes is generally inappropriate for fracture critical, damage tolerant AM parts.**
- 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 region along with the CIFS.

Qualification & Certification/NASA MSFC Guidance

- 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 demonstration parts with simulated CIFS defects are used to demonstrate NDE detection capability.
- **NDE standard defect classes for welds and castings welding or casting defect quality standards will generally not be applicable**

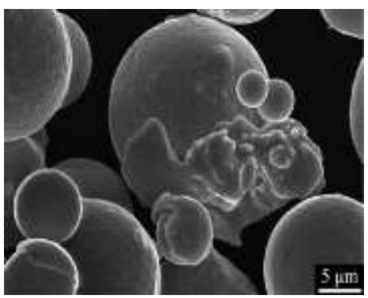
- Relevant AM process defect types used must be considered.
- AM processes tend to prohibit volumetric defects with significant height in the build (Z) direction. The **concern instead is for planar defects**, such as aligned or chained porosity or even laminar cracks, that form along the build plane. 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.**

Structural Margin Criteria

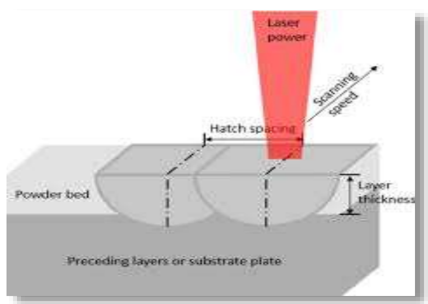
Material Property	Criteria for High Structural Margin
Loads Environment	Well defined or bounded loads environment
Environmental Degradation	Only due to temperature
Ultimate Strength	30% margin over factor of safety
Yield Strength	20% margin over factor of safety
Point Strain	Local plastic strain < 0.005
High Cycle Fatigue, Improved Surfaces	4x additional life factor or 20% below required fatigue limit cyclic stress range
High Cycle Fatigue, As-built Surfaces	10x additional life factor or 40% below required fatigue limit cyclic stress range
Low Cycle Fatigue	No predicted cyclic plastic strain
Fracture Mechanics Life	10x additional life factor
Creep Strain	No predicted creep strain

Qualification & Certification/Qualified Metallurgical Process

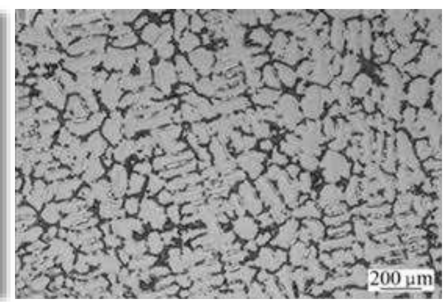
- Draft NASA MSFC Standard identifies AM as a unique material product form and requires the metallurgical process to be qualified on ***every*** individual AM machine
- Developed from internal process specifications with likely incorporation of forthcoming industry standards.



Powder



Process Variables



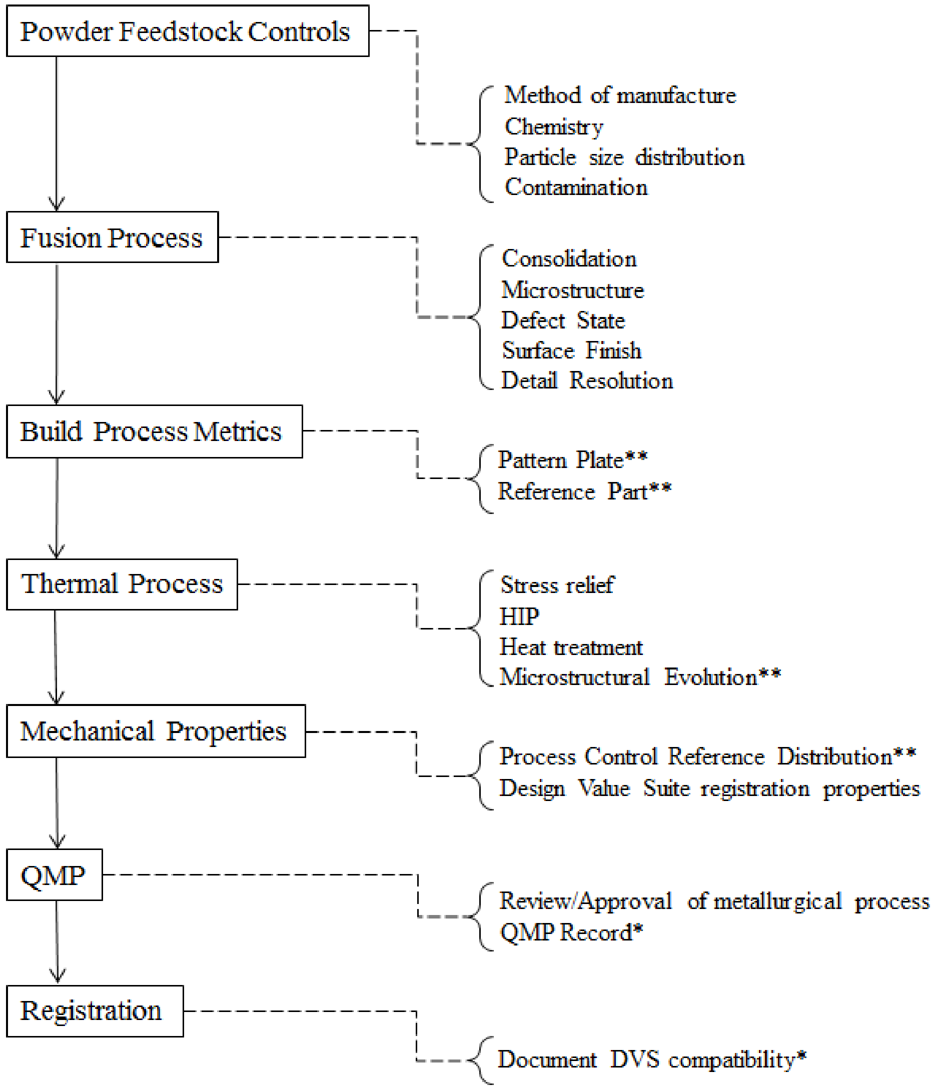
Microstructure

Properties

Qualification & Certification/Qualified Metallurgical Process

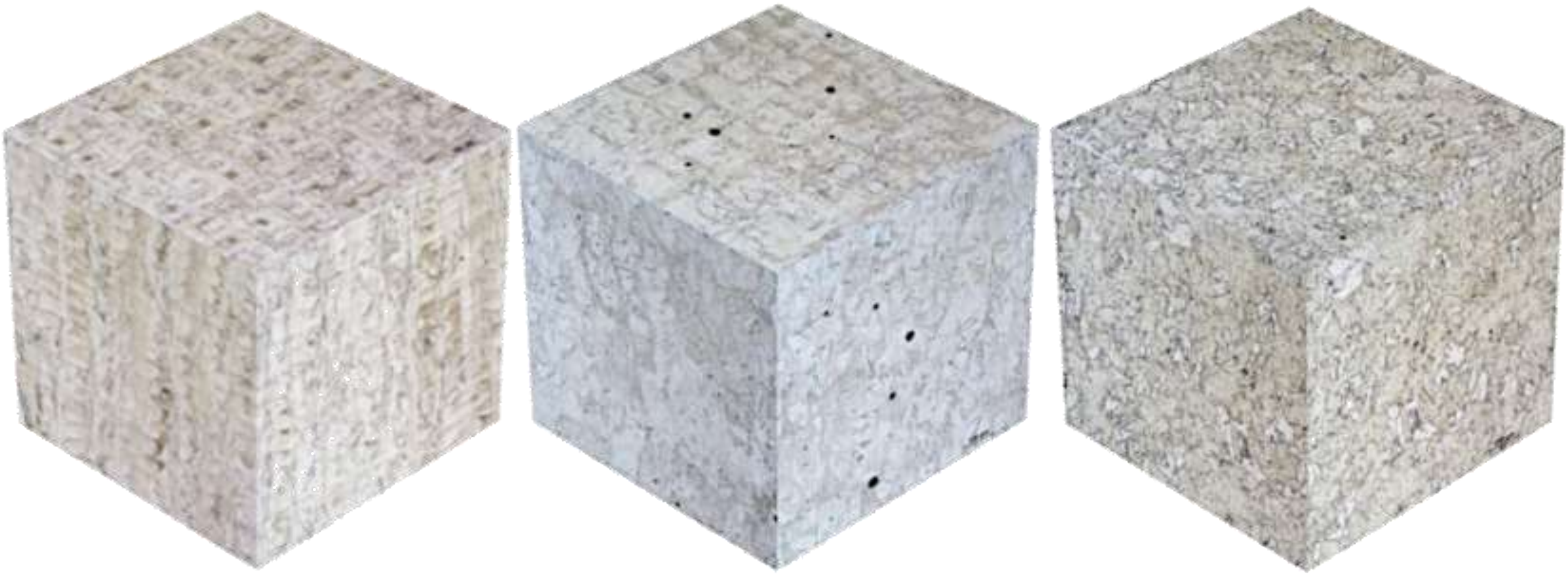
QMP:

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



*Quality management system record

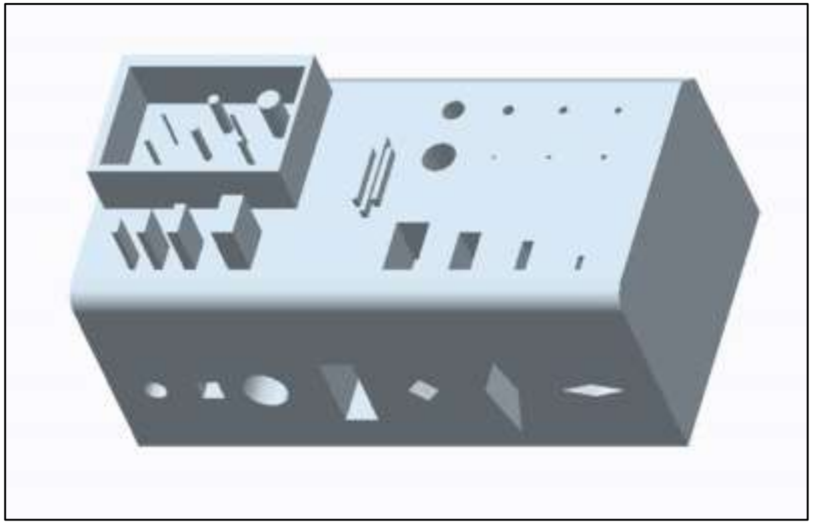
**Acceptance criteria metric

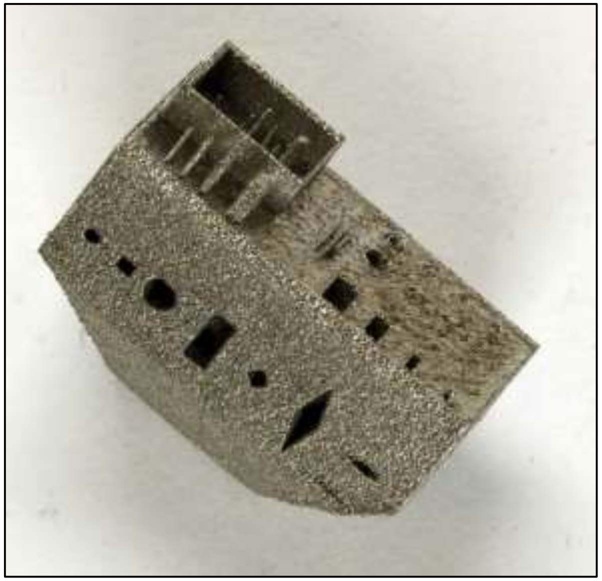


As Built　　Stress Relieved　　HIP & Final

Qualified Metallurgical Process (QMP)

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





Reference parts:

Metrics for surface texture quality and detail rendering

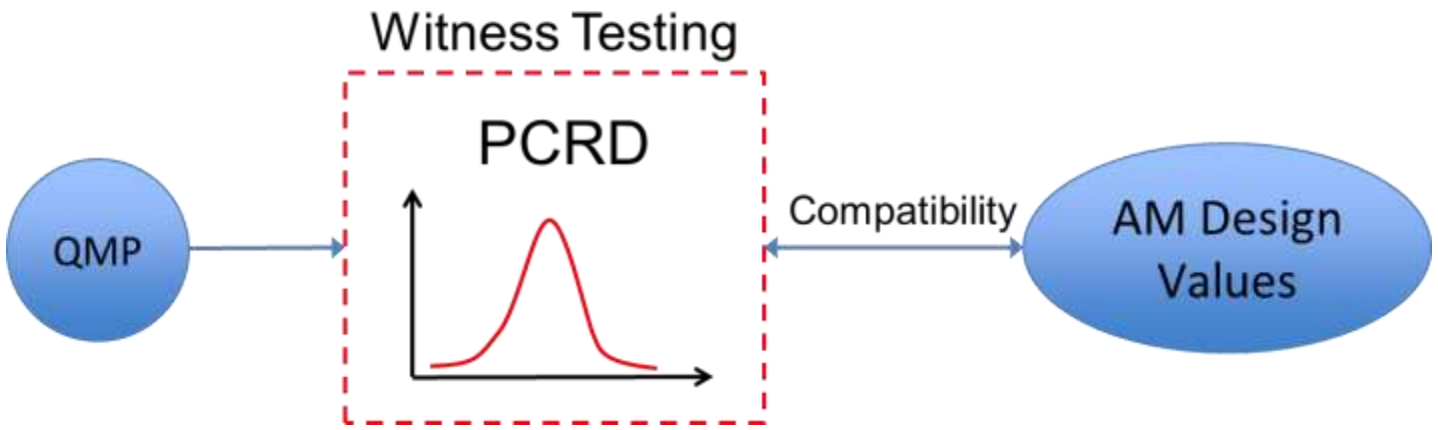
Overhanging, vertical and horizontal surface texture, acuity of feature size and shape

Qualified Metallurgical Process (QMP)

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

Qualification & Certification/Qualified Metallurgical Process

- Mechanical behavior reference data
  - Strength, ductility, fatigue performance
  - Process Control Reference Distributions (PCRD)
- Establish and document estimates of mean value and variatio 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



Types of AM build witness specimens

- Metallurgical
- Tensile (strengths 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 in-direct indicator of AM part quality through inference.

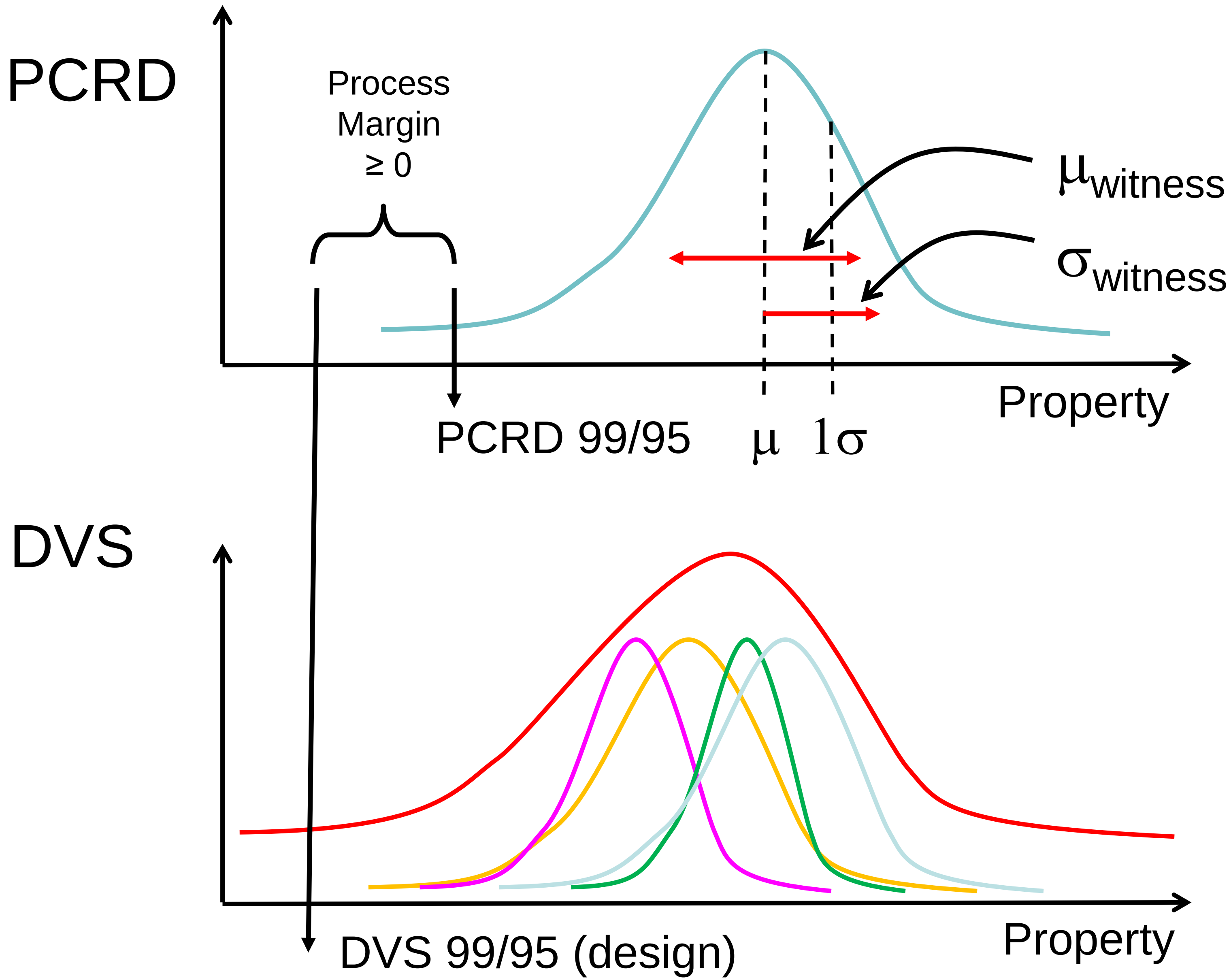
Mechanical Property Witness Procedures

- 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

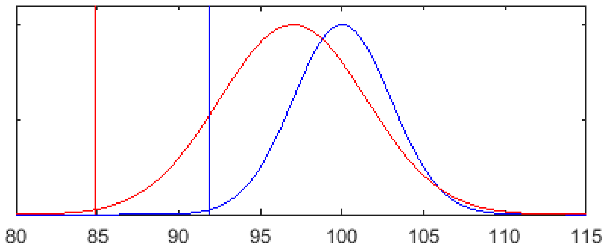
- **Ongoing evaluation of material quality substantiates the design allowable**
- **Only plausible way to maintain design values**

Qualification & Certification/Qualified Metallurgical Process

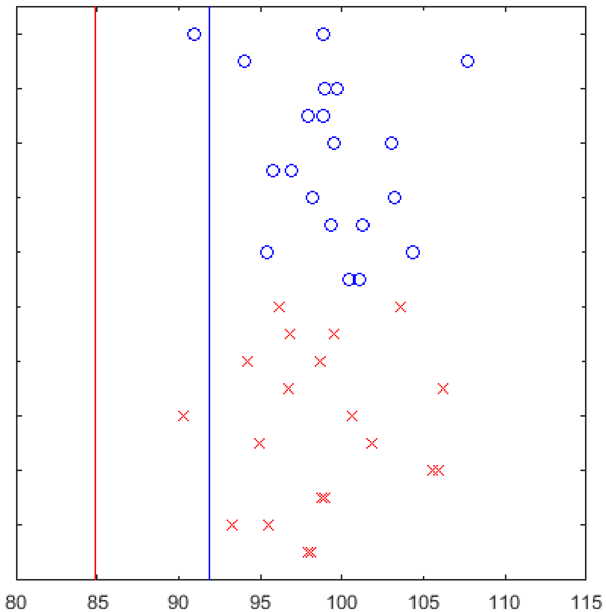


Example of AM build witness specimen evaluations

Nominal process is blue, off nominal in red



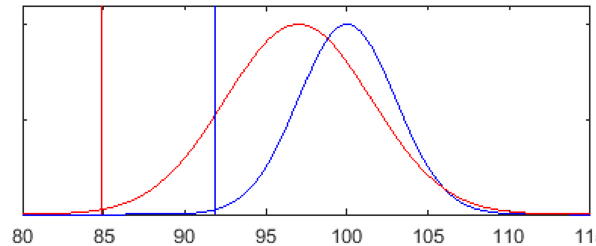
Two (2) witness tests per build



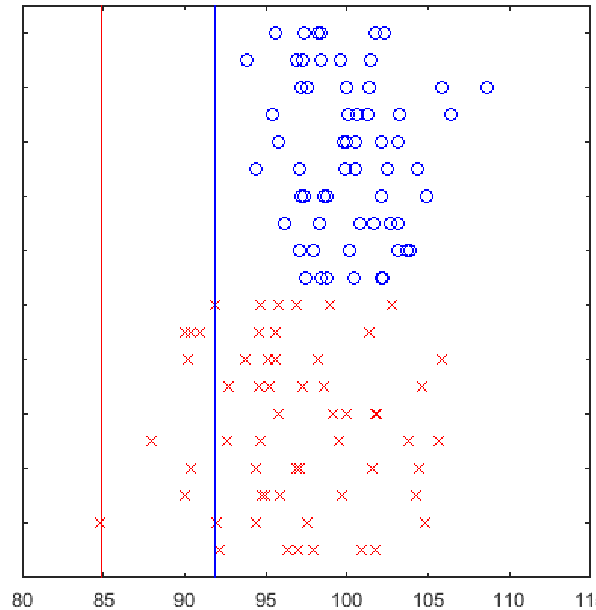
Process shift hard to discern

Random draw from nominal process 10 times

Random draw from off-nominal process, 10 times



Six (6) witness tests per build

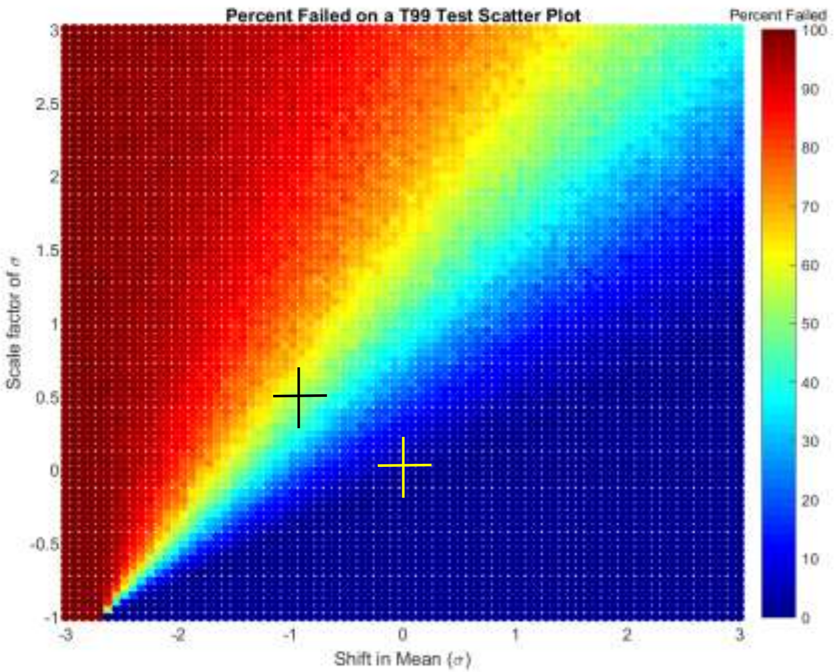


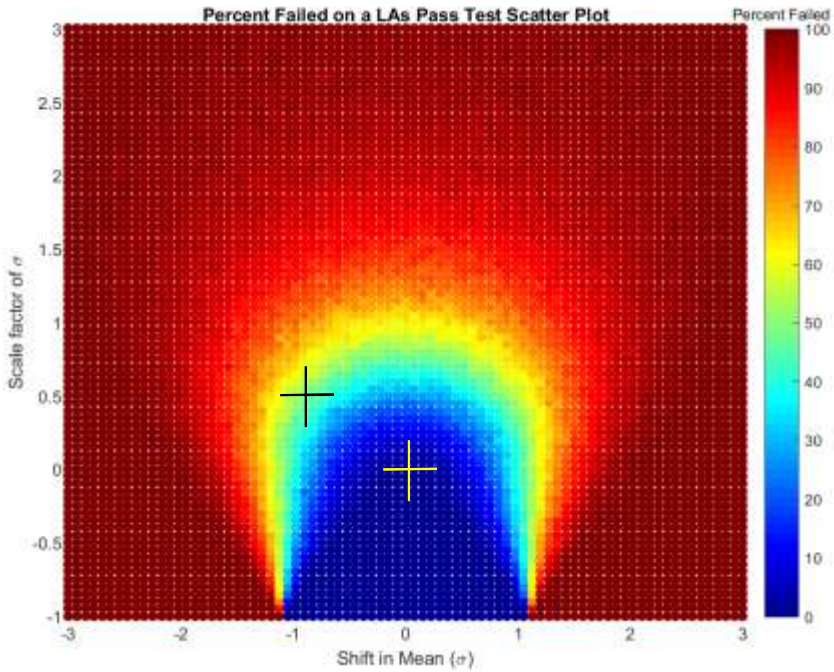
Process shift discernable with analysis of mean and variation

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

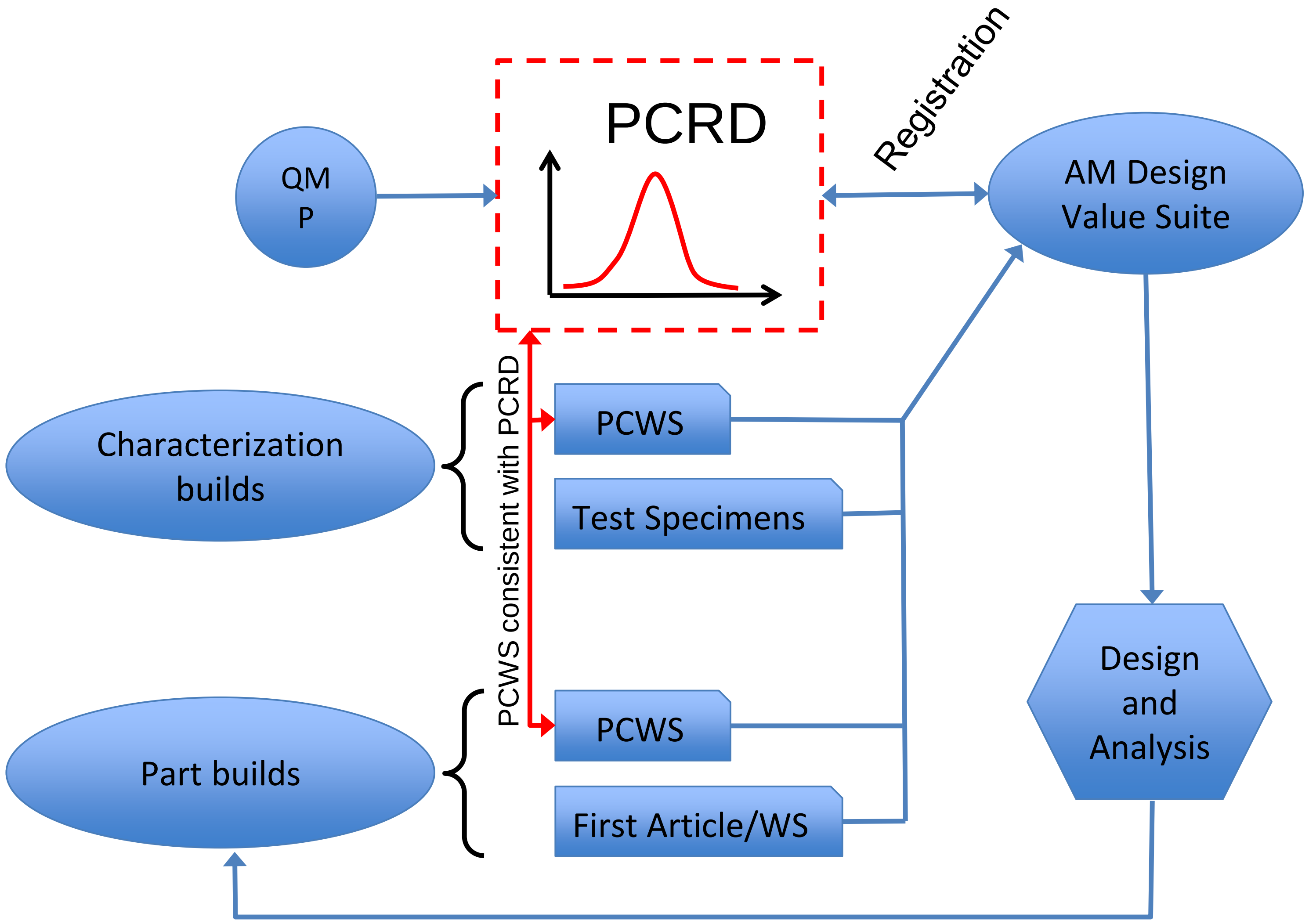
Design acceptance criteria for the following:

- Keep process in family
- Minimize false negative acceptance results
- Protect the design values witnessed
- Protect the inferred design values





Qualification & Certification/Witness for Statistical Process Control



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

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 SLM 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.

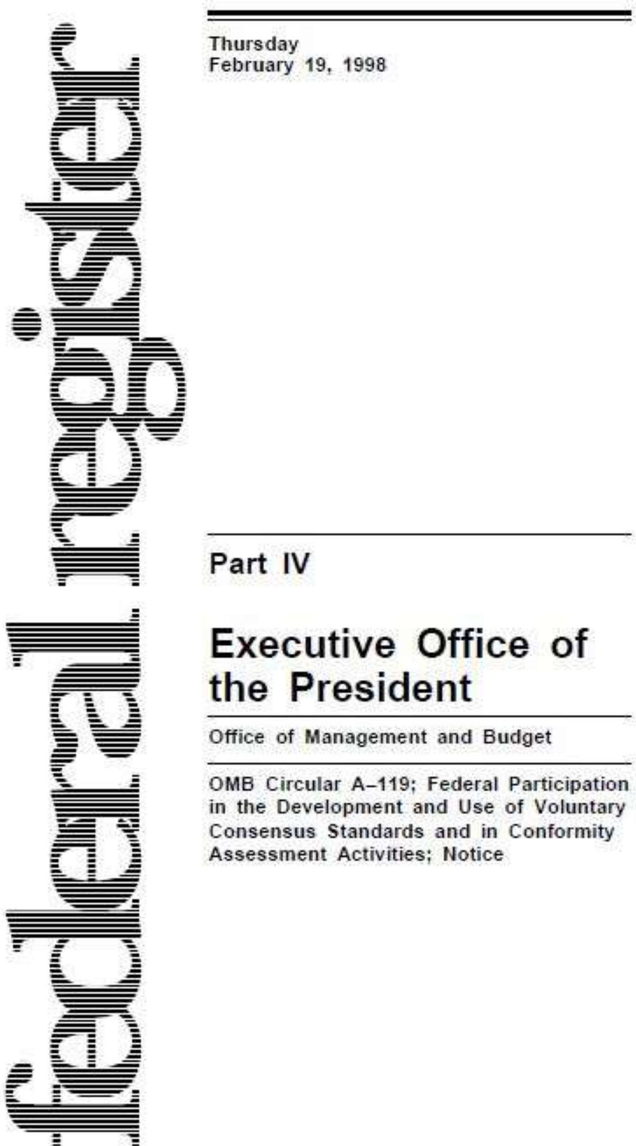
Qualification & Certification/AM Qualification Challenges

- 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**

OMB A-119


federal register

Thursday
February 19, 1998

Part IV

Executive Office of the President

Office of Management and Budget

OMB Circular A–119; Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities; Notice

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

- NASA: improve mission reliability and safety

- Industry: boost business and develop technology for American commerce

Similar NDE of AM U.S./E.U. Efforts

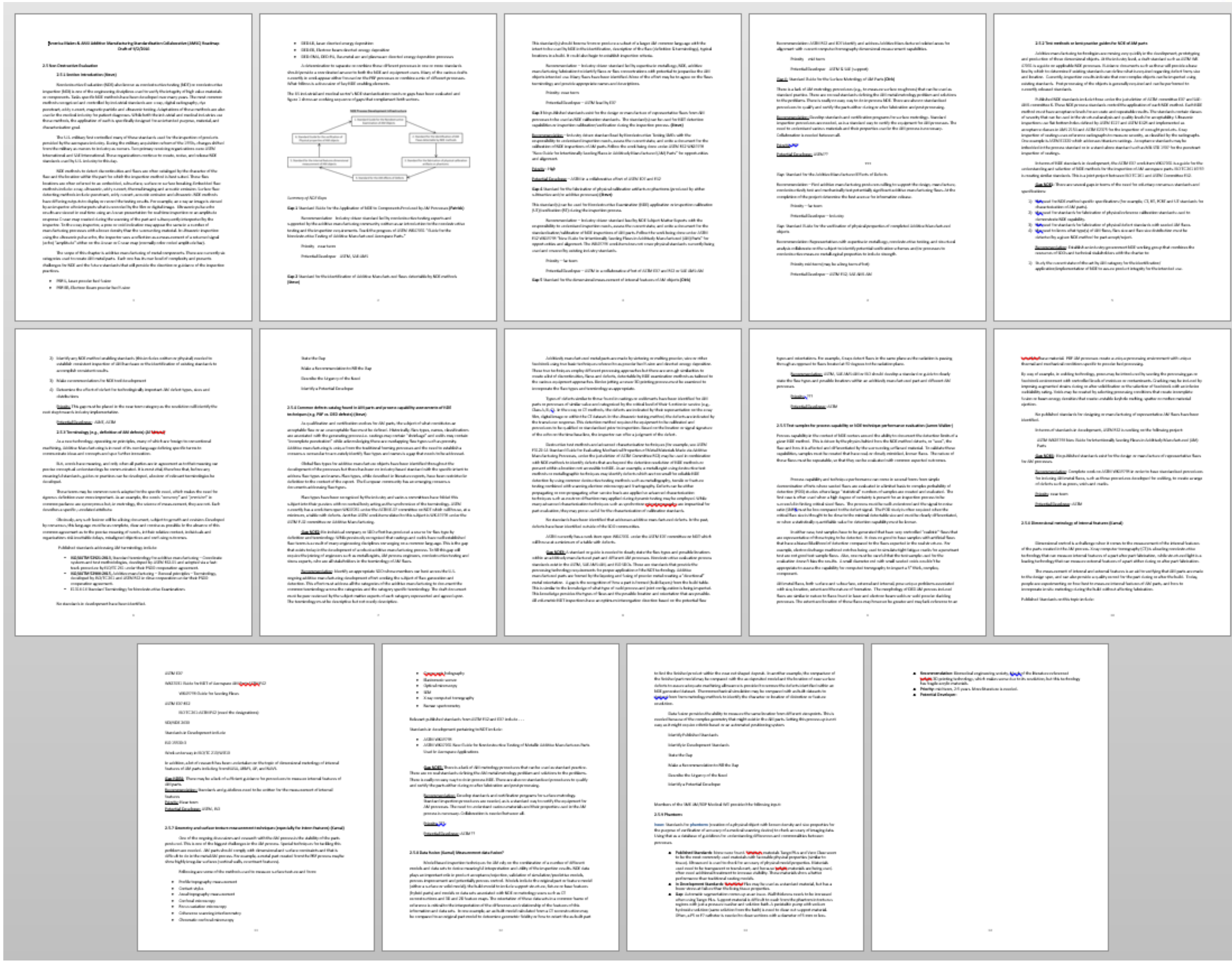
- Status on ISO TC 261 JG 59 standard for NDT of AM products

ASTM E07.10 WK47031 NDT of AM Guide

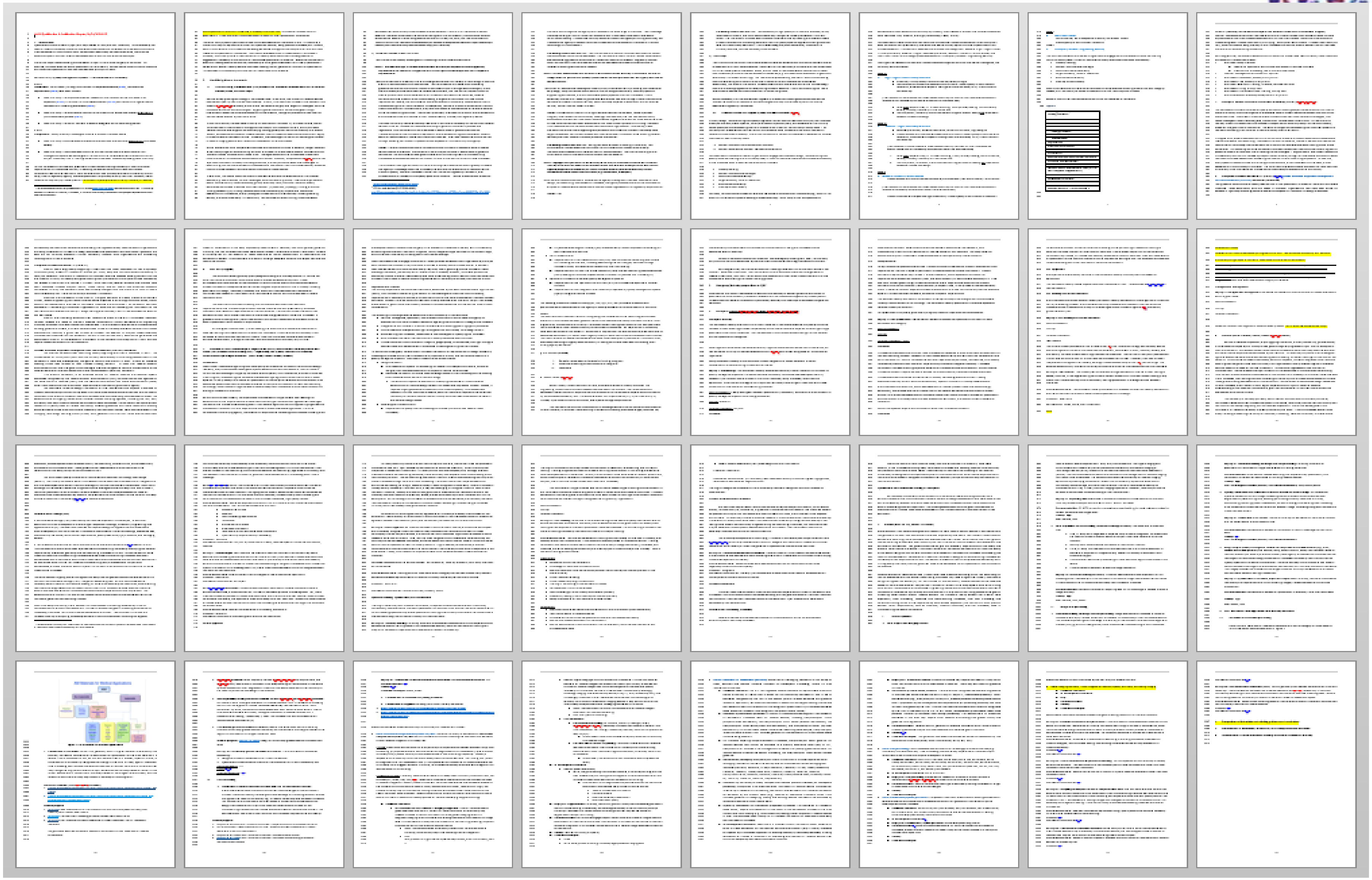
ISO TC 261 JG59 Best NDE Practice

- First VCO catalogues of AM defects showing Defect ↔ NDE linkage
- No agreement between ISO TC261 JG59 and E07 to develop joint standards
- ASTM WK47031 references U.S. standards; ISO standard references ISO standards

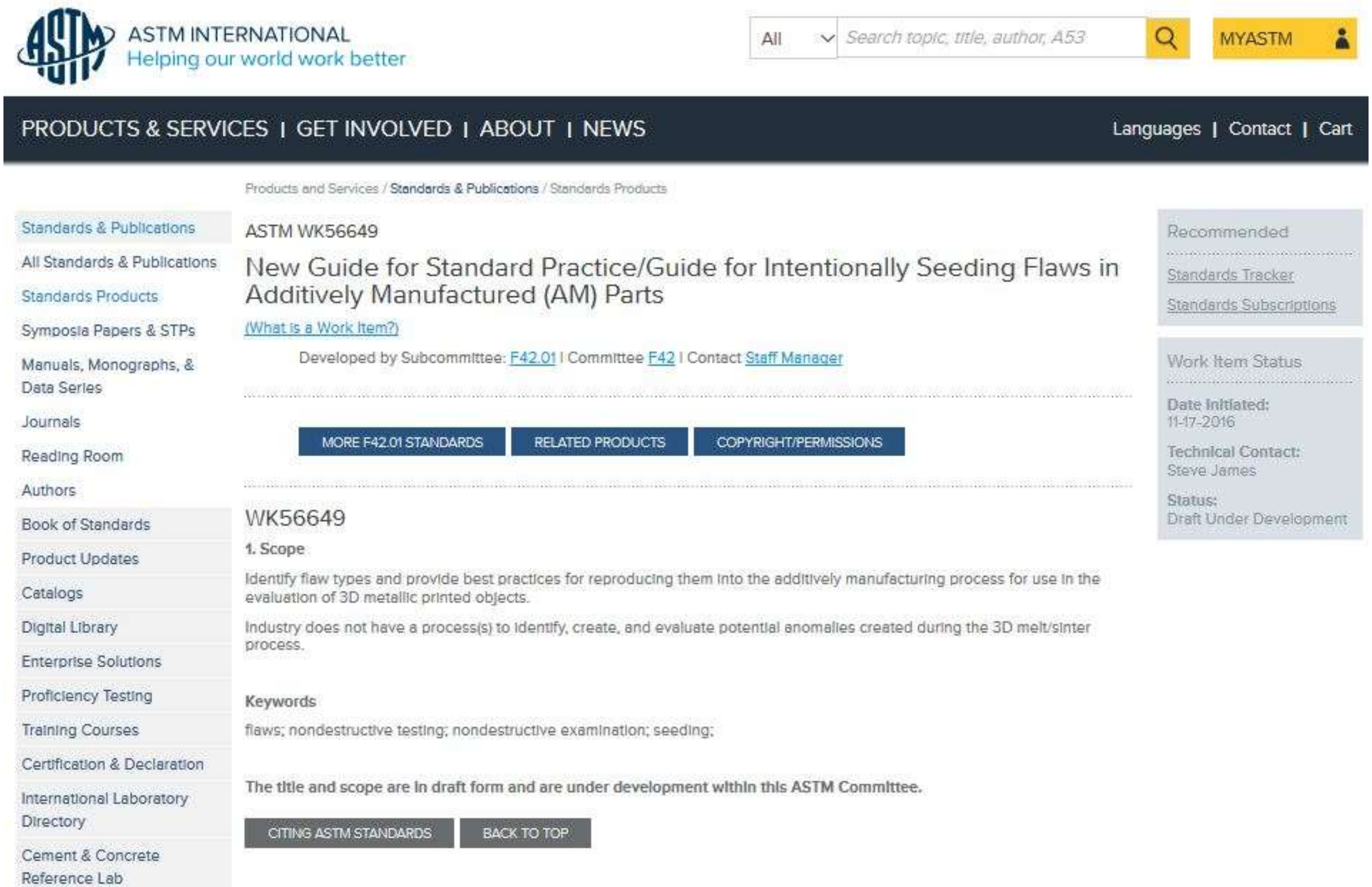
AMSC Nondestructive Evaluation Working Group Roadmap – 9/2/16 draft



AMSC Qualification and Certification Working Group Roadmap – 9/14/16 draft



- 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

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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.

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Recommended

- Standards Tracker
- Standards Subscriptions

Work Item Status

Date Initiated:
11-17-2016

Technical Contact:
Steve James

Status:
Draft Under Development