



NASA OSMA NDE Program Additive Manufacturing Foundational Effort

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

NASA QUALITY ASSURANCE IN ADDITIVE MANUFACTURING (AM)
A WORKSHOP ON ASSURING AM PRODUCT INTEGRITY

October 11-12, 2016

Beckman Auditorium, California Institute of Technology, Pasadena CA

Background

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



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

Background

NASA/TM—2014—218560



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

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Prepared for

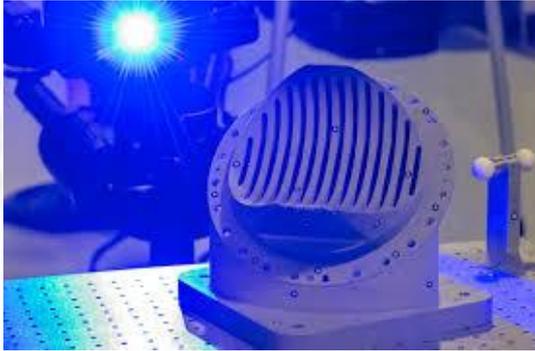
Edward R. Generazio
National Aeronautics and
Space Administration

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Hampton, Virginia

November 2014

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

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



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



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



EBF³ wire-fed system during parabolic flight testing



28-element Inconel 625 fuel injector



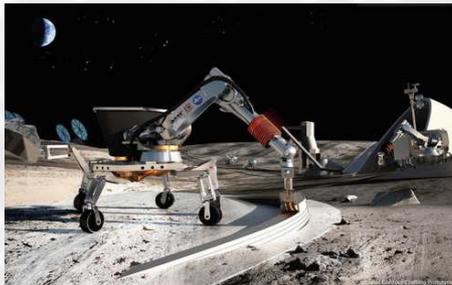
Prototype titanium to niobium gradient rocket nozzle



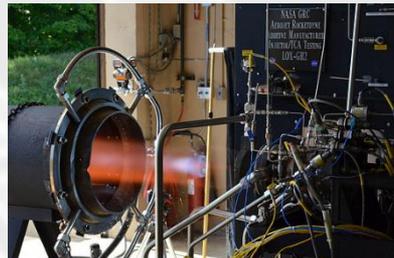
Made in Space AMF on ISS



SpaceX SuperDraco combustion chamber for Dragon V2



ISRU regolith structures



Aerojet Rocketdyne RL-10 engine thrust chamber assembly and injector



Dynetics/Aerojet Rocketdyne F-1B gas generator injector



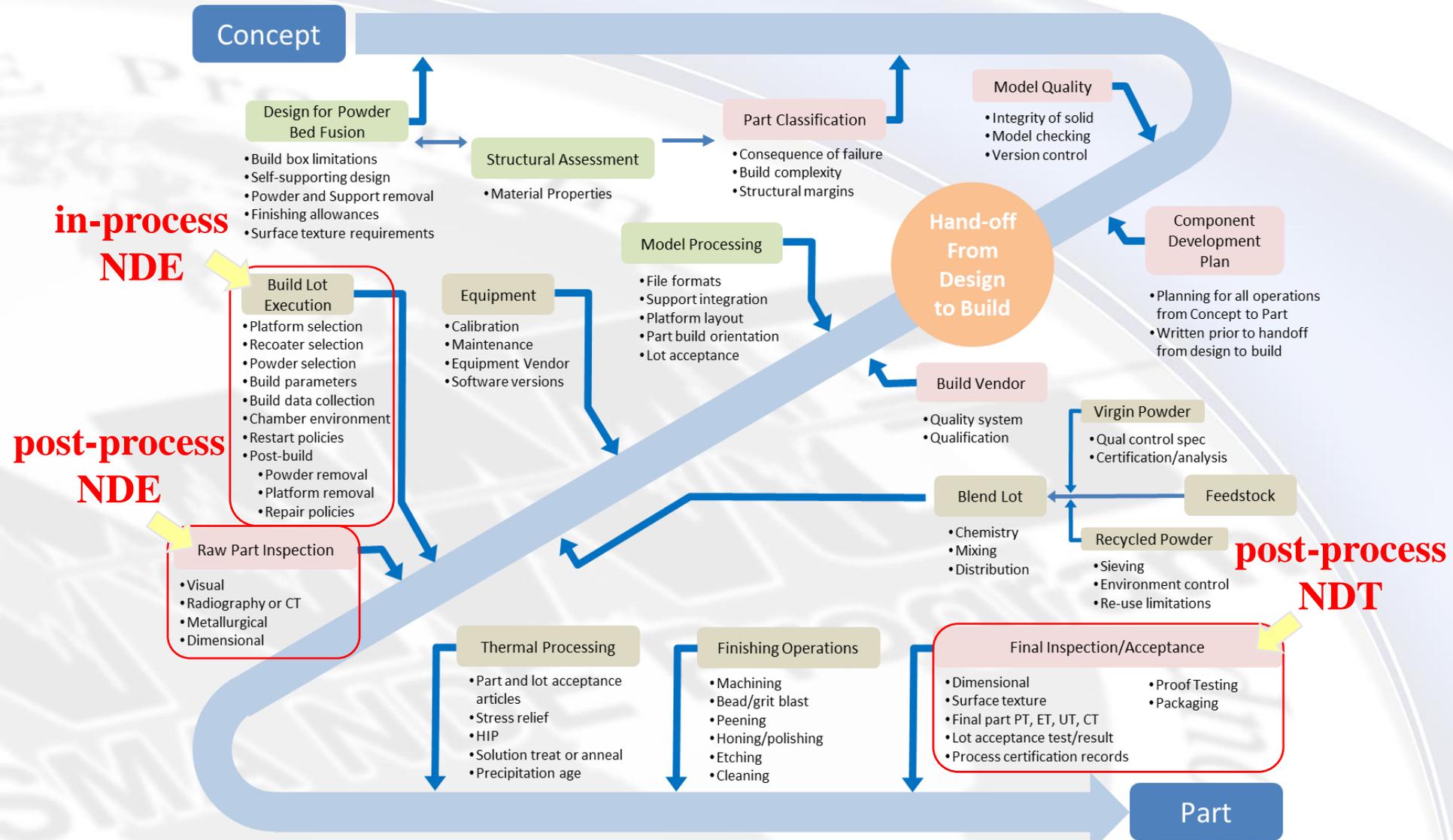
NDE of AM Technology Gaps

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

Develop and Capture Best NDE Practice

NDE of AM Technology Gaps

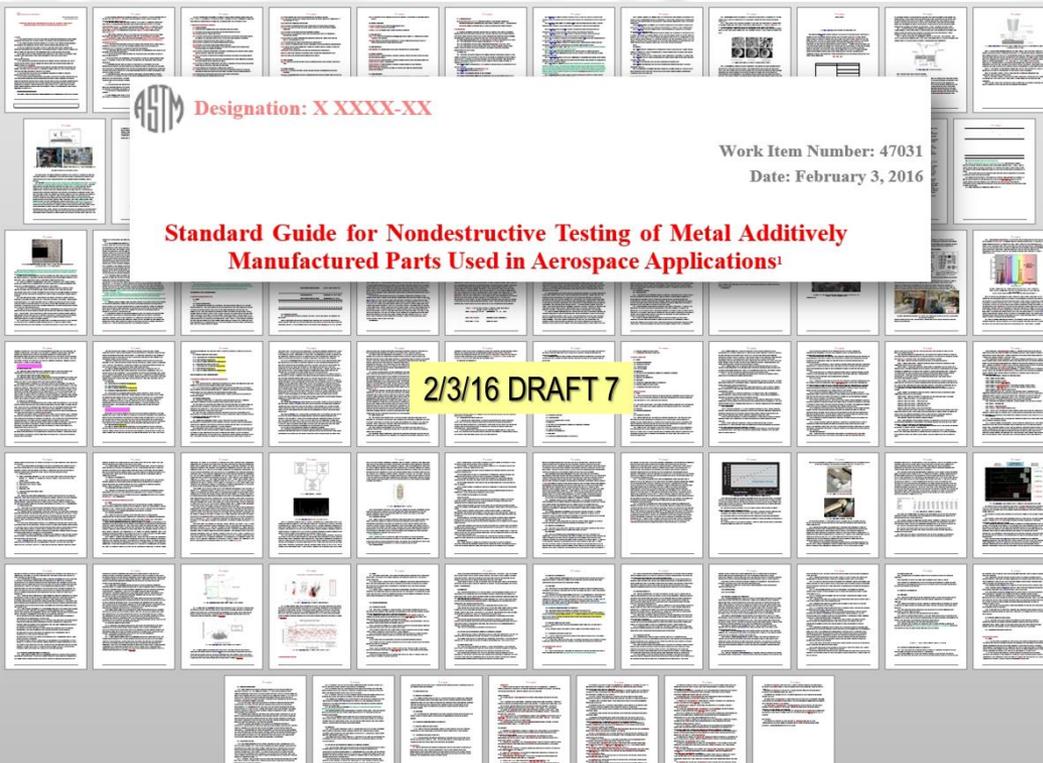
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ASTM WK47031, NDE of metal parts used in aerospace applications (NASA leadership)

ASTM E07.10 WK47031 NDE of AM Guide

ISO TC 261 JG59 Best NDE Practice



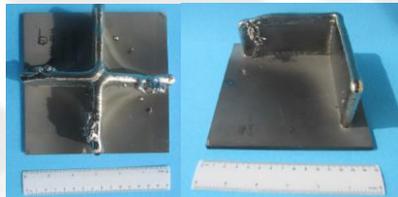
- First defect catalogues to show defect ↔ NDE linkage
- Process method determines defects
- Defect type & part complexity determine NDE selection

Coordinated by S. James (Aerojet Rocketdyne)

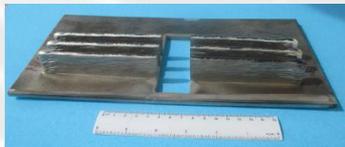
Electron Beam Freeform
Fabrication (EBF³)
Inconel 625 on copper



Ti-6Al-4V (4)



SS 316

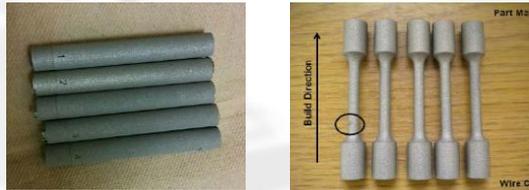


Al 2216



Selective Laser Melting
(SLM)

Ti-6Al-4V bars Al-Si-10Mg dog bones



Inconel 718 inserts (6)
w/ different processing history

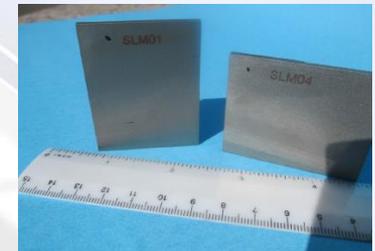


Inconel 718 prisms
for CT capability demonstration



Electron Beam Melting
(EBM)

SS 316 PT/RT panels
w/ EDM notches



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

Identify Relevant Defects

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.

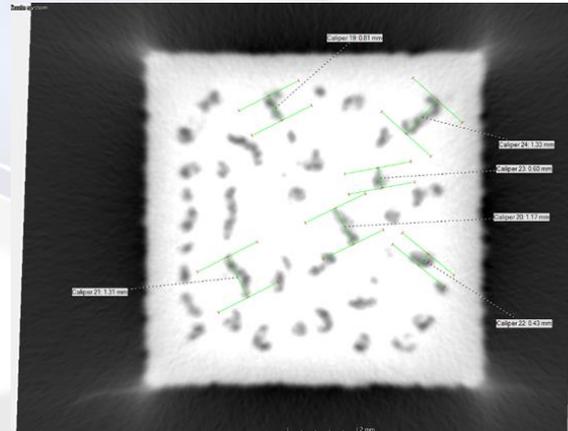
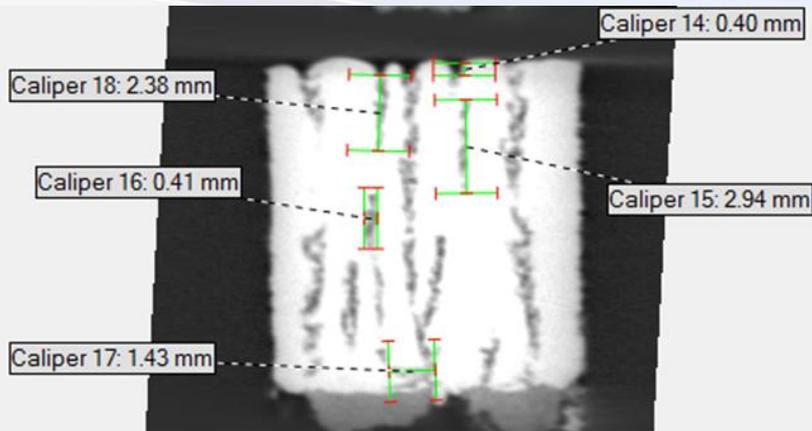
		Non- NDT	Common in DED & PBF	Covered by current standards	Unique to AM
Flaw type					
DED	Poor surface finish	■	■		
	Porosity		■	■	
	Incomplete fusion			■	
	Lack of geometrical accuracy/steps in part	■	■		
	Undercuts			■	
	Non-uniform weld bead and fusion characteristic		■	■	
	Hole or void		■	■	
	Non-metallic 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

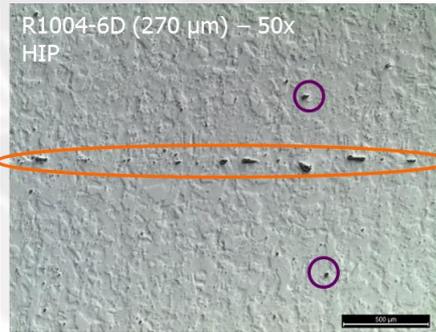
§ ISO TC 261 JG59, Additive manufacturing – General principles – Nondestructive evaluation of additive manufactured products, under development.

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

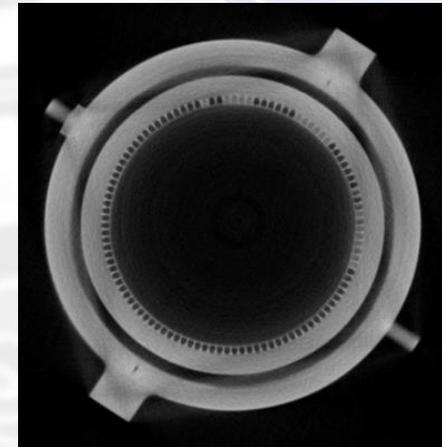




Cross layer

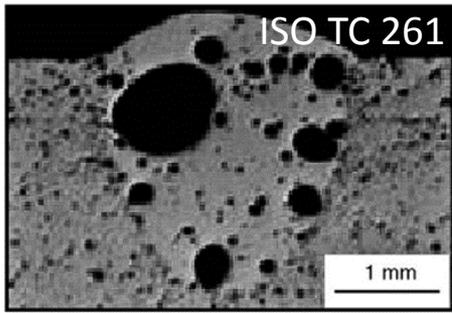


Layer

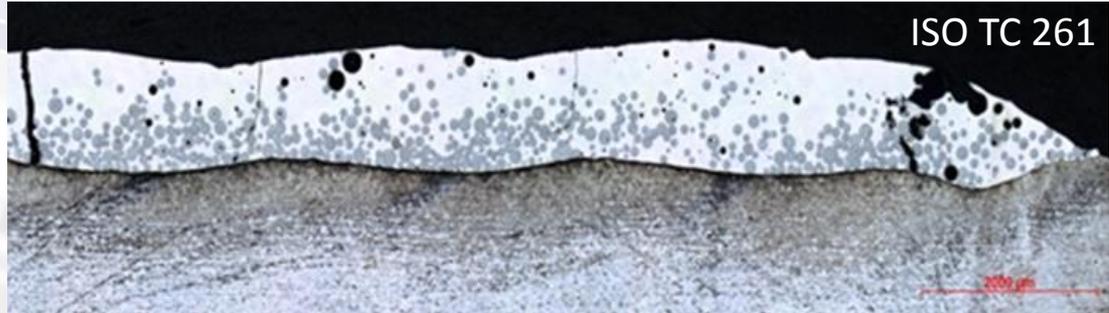


Trapped Powder

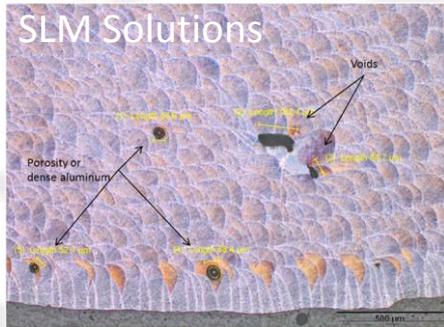
Also have unconsolidated powder, lack of geometrical accuracy/steps in the part, reduced mechanical properties, inclusions, gas porosity, voids, and poor or rough surface finish



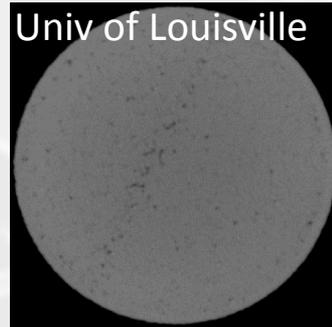
PBF Porosity



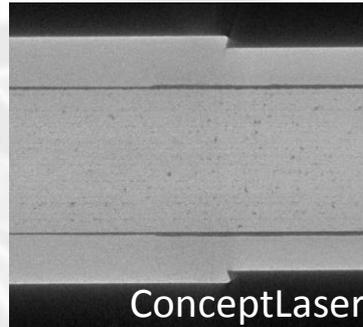
DED Porosity



Porosity and Voids

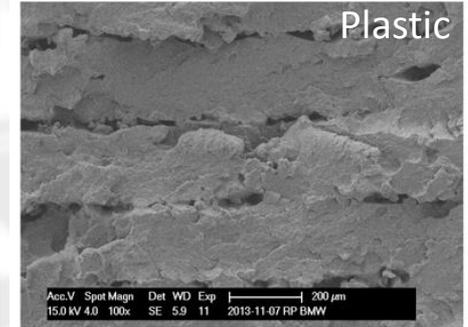


Univ of Louisville



ConceptLaser

Voids



Plastic

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.

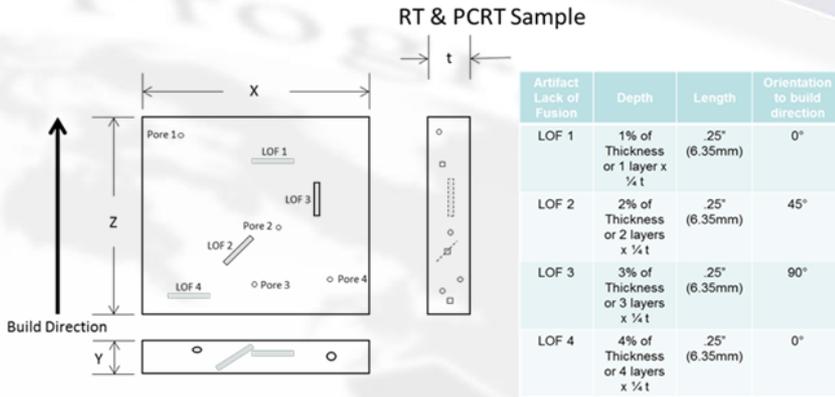
voids, n—flaws created during the build process that are empty or filled with partially or wholly un-sintered or un-fused powder or wire creating pockets. Voids are distinct from gas porosity, and are the result of lack of fusion and skipped layers parallel or perpendicular to the build direction. Voids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

Demonstrate NDE Capability

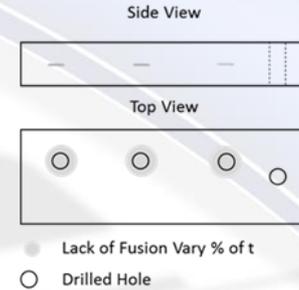
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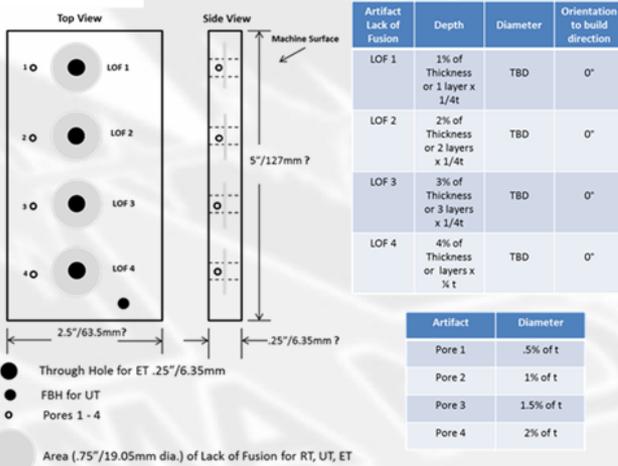
Demonstrate NDE capability



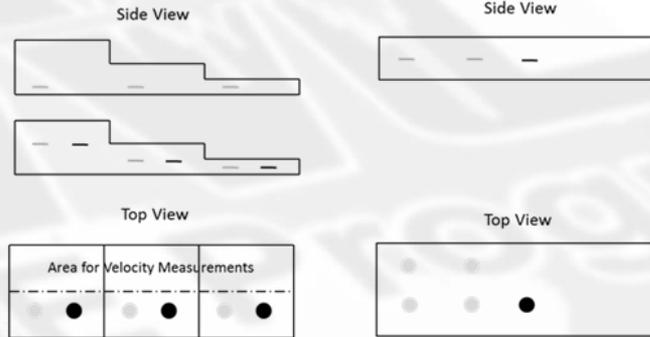
ECT Sample



Multiuse Sample (MUS)



UT Sample
Stepped vs. One Thickness

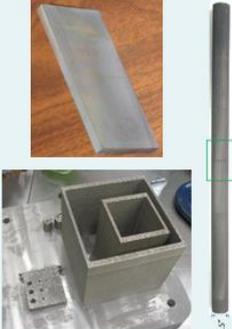
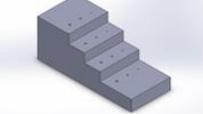
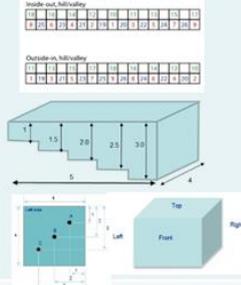
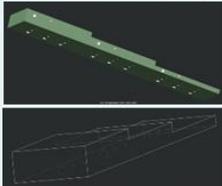


PT Sample
Fatigue Crack or Surface Texture



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

Demonstrate NDE capability

	MSFC-GRC	GSFC	LaRC	JSC-LaRC	KSC
AM process method	DMLS	DMLS (metal), LS (plastic)	LS	EBF ³	EBM
alloys	titanium, Inconel, and aluminum	titanium, SS PH1, vero-white RGD835	SS	titanium	titanium
reference standard geometries			Conventional:  AM (planned): 	wrought (JSC) and AM (LaRC): 	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 μ CT; 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

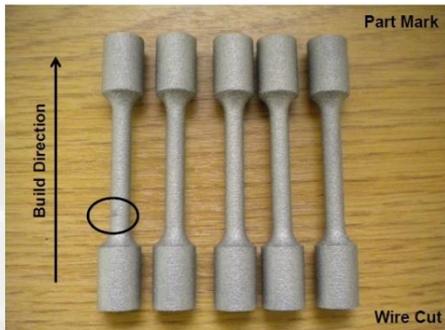
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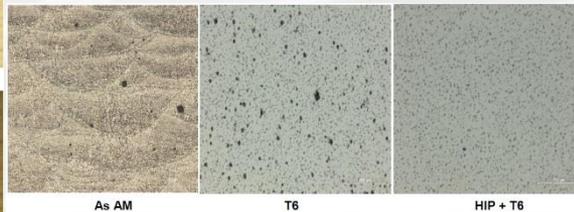
Determine effect-of-defect on sacrificial specimens with seeded flaws

Airbus Laser Powder Bed Fusion (PBF) samples

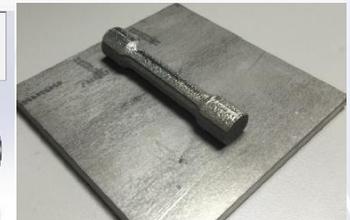
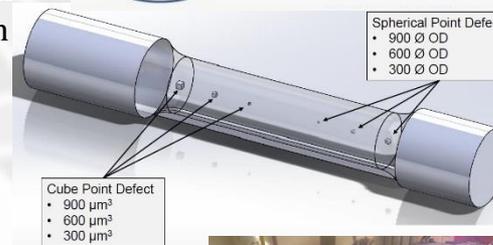
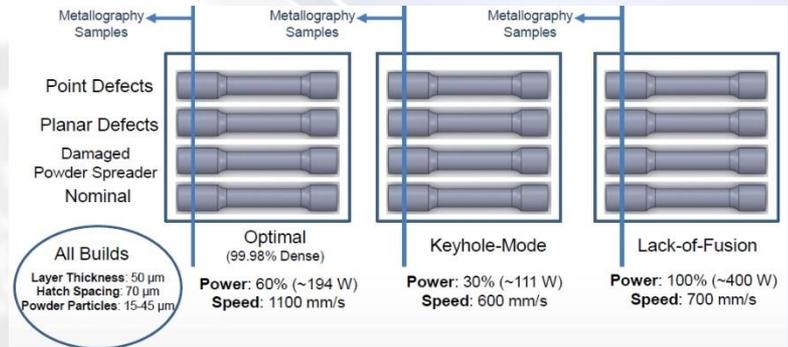
Advratech Laser PBF samples (in progress)



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



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



- § FY17 STTR T12.04-9941 Real-Time Geometric Analysis of Additive Manufacturing status (NASA MSFC) Develops a novel process control and part documentation solution for selective laser melting (SLM) additive manufacturing (DECLINED).
- FY17 STTR T12.04-9979 Metal Digital Direct Manufacturing (MDDM) for Close-Out of Combustion Chambers and Nozzle Fabrications. Sub-scale and intermediate size nozzles will be fabricated using hybrid MDDM processes and delivered to the NASA-MSFC for hot fire testing (APPROVED)



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

Qualify & Certify NASA AM Hardware

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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
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Contact: *Doug Wells (MSFC)*

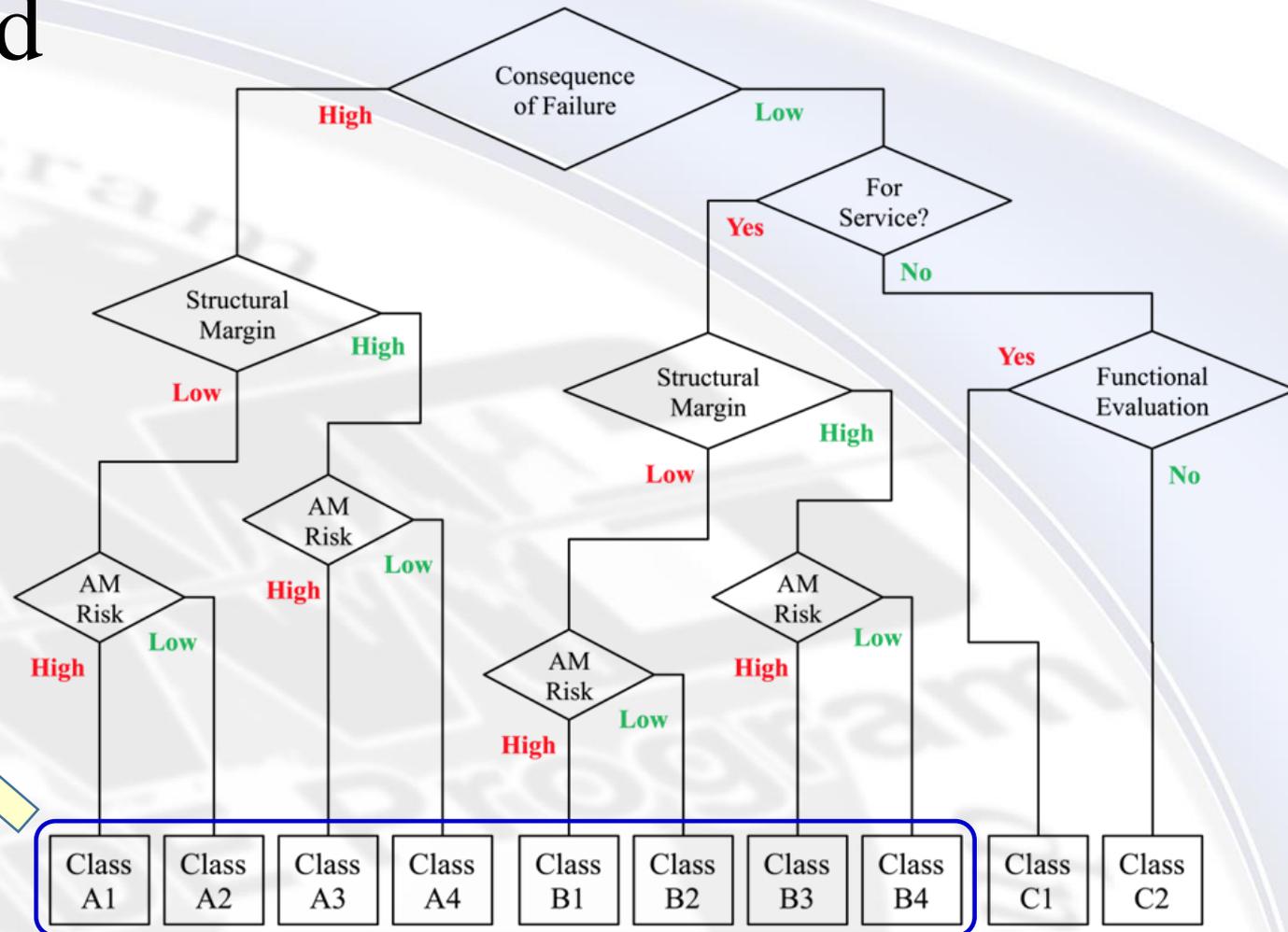
- Comprehensive draft technical standard is in review
- All Class A and B parts are expected to receive comprehensive NDE for surface and volumetric defects within the limitations of technique and part geometry
- Not clear that defect sizes from NASA-STD-5009[§] are applicable to AM hardware
- NDE procedural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

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



Background

Comprehensive NDE required for surface and volumetric defects



[§] 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.

Qualification & Certification

- 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

- 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**

Qualification & Certification

- 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.**

Determine Rejection Thresholds for Critical Defects

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.

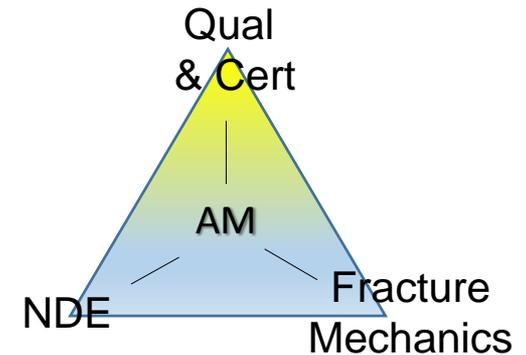
For more information please visit: <http://www.astm.org/E08RTD5-2016>

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

Hannah Sparks
Administrative Assistant, Symposia Operations

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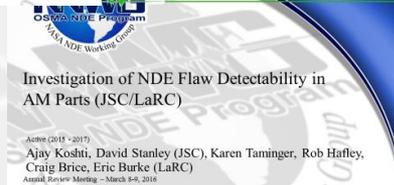
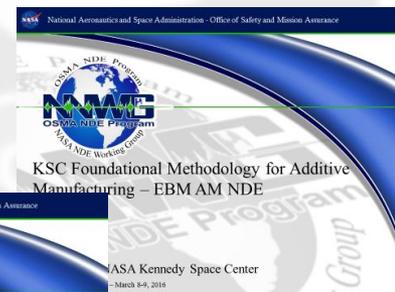
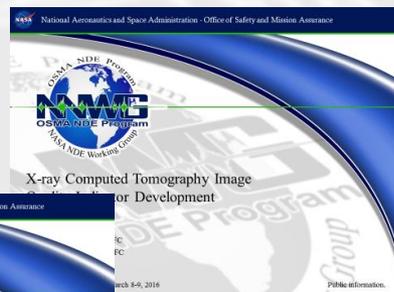
Address:

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

Current NASA Efforts Related to NDE of Additive Manufacturing

FY16 Continuing Projects

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



FY17 New Starts

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



- Effect-of-Defect of Unique Laser Powder Bed Fusion Flaw Types: NASA-Industry Round Robin Study (Waller, Nichols)



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

Initial Evaluation	Steven J. Gentz
	April 21, 2016

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

Steven J. Gentz
April 21, 2016

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2



**America Makes/ANSI
Additive Manufacturing
Standardization Collaborative
(AMSC)**



**America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)
Working Group (WG) Architecture and Co-Chairs
(updated 5/13/16)**

Below is the evolving list of WGs and their co-chairs, and issues that they will be addressing in terms of identifying existing or needed standards and specifications. Participants are invited to sign up for one or more groups using the sign-up sheet. The working groups are holding online meetings every two weeks. (Note: Specific meeting times should be confirmed with ANSI as recurring meeting times listed below are subject to change on specific dates when there are holidays or other conflicts that may necessitate re-scheduling.)

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 documentation (Neutral build file, Product definition data sets)

Validation

Process and Materials WG*

Meets: Every 4th Tuesday, 11 am – 12 noon Eastern, beginning May 24, 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





**America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)
Working Group (WG) Architecture and Co-Chairs
(updated 5/13/16)**

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

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

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

Finished Materials SG
Meets: Every other
Thursday, 1-2 pm Eastern,
beginning May 12, 2016
Leader: TBD

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

Equipment
Digital format
Calibration
Parameter control
Powder handling
Powder reuse/recycle
Operator training
Safety
Machine qualification

Heat Treat
HIP
Surface finishing
Machining
Hybrid machines
Removal of Support Materials

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

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

Ensure that all stages of a particular AM process have 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 for all aspects of AM (variability, repeatability, suitability, etc.)





**America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)
Working Group (WG) Architecture and Co-Chairs
(updated 5/13/16)**

**Non-Destructive Evaluation (NDE) WG
Meets: First Meeting May 20, 2016 at 1 pm Eastern
Co-chairs: TBD**

**Scope: NDE of Finished Parts
Test methods or best practice guides for NDE of AM parts
Common defects found in AM parts and Probability of Detection (PoD) assessments of NDE techniques
Test samples for PoD or NDE technique performance evaluation
Geometry and surface texture measurement techniques (especially for internal features)
Gaps in current NDT methods
AM defects terminology
Intentionally seeding AM flaws**

**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**

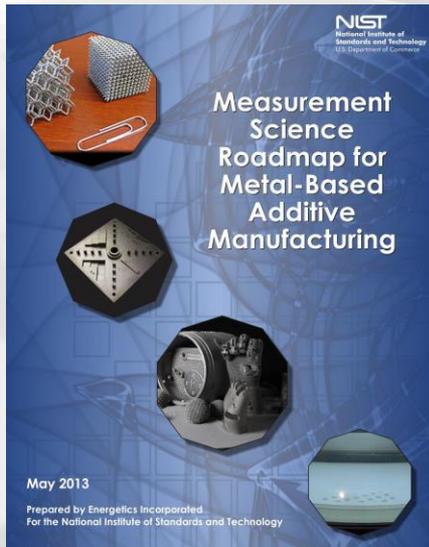


The image displays a grid of 32 document pages, organized into 4 rows and 8 columns. Each page contains text, likely representing different sections of a roadmap. The text is dense and includes various formatting elements such as bullet points, numbered lists, and bolded text. Some pages feature tables or diagrams. For example, the top-right page contains a table with multiple rows and columns. The bottom-left page features a flowchart with several boxes and connecting lines. The overall layout is a structured grid of document pages.

THIS IS ONLY THE BEGINNING



Back-ups



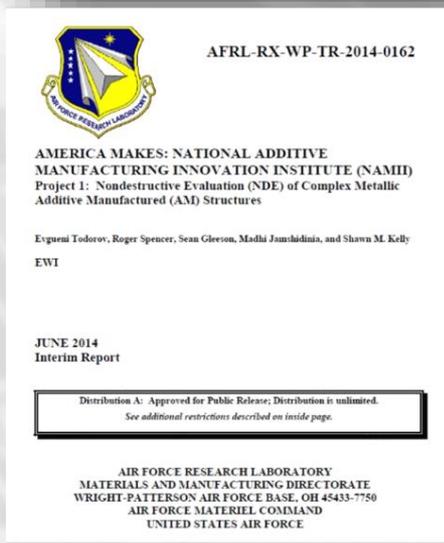
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NASA AM Foundational Effort

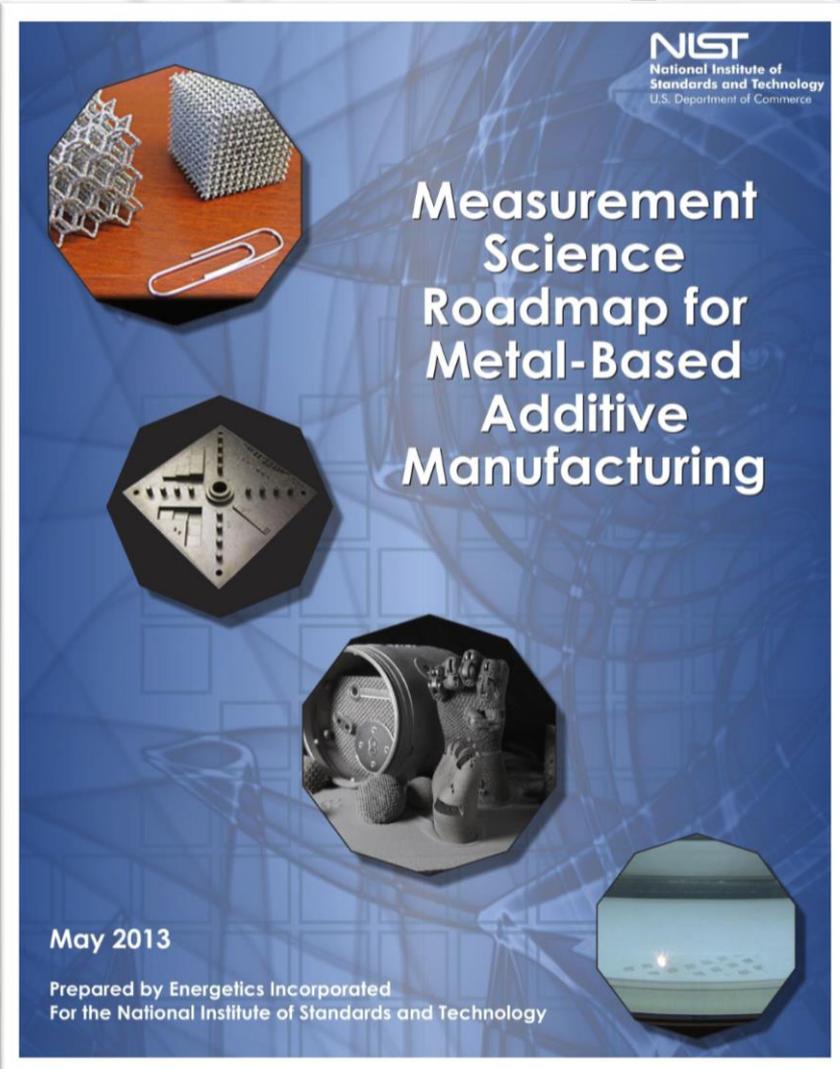
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Technological Acceptance and Increased Utilization

↑ ↑



NIST Roadmap



Contact: *Kevin Jurrens (NIST)*

- Technology challenges impede widespread adoption of AM
- Measurement and monitoring techniques, including NDE, cut across all aspects of AM, from input materials to processing to finished parts
- Ways to fully characterize AM parts, including NDE, are needed to insure processing effectiveness and part repeatability (part certification)
- NASA participation
 - Matt Showalter, GSFC
 - Karen Taminger, LaRC
 - Gary Wainwright, LaRC
 - Nancy Tolliver, MSFC

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

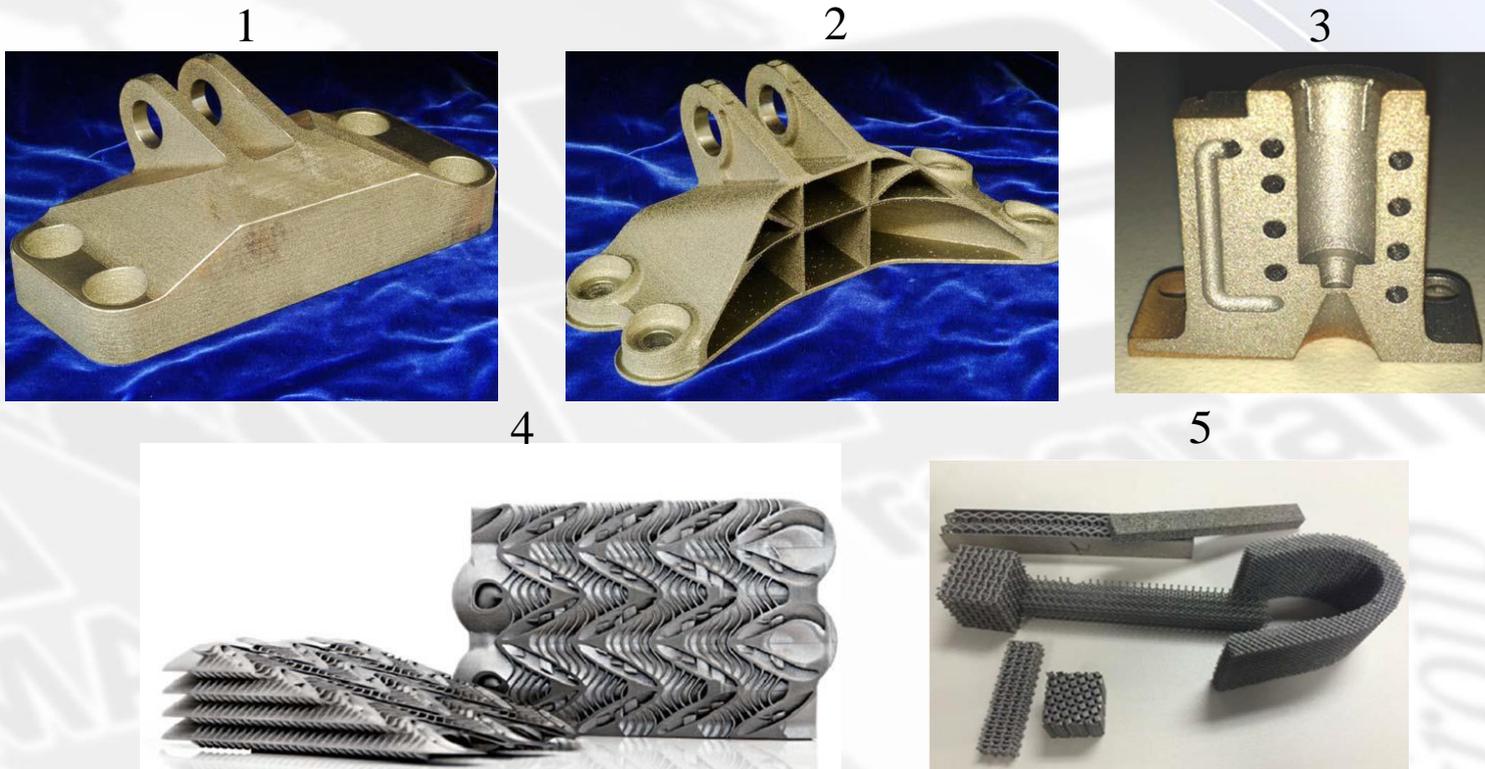
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AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

- 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

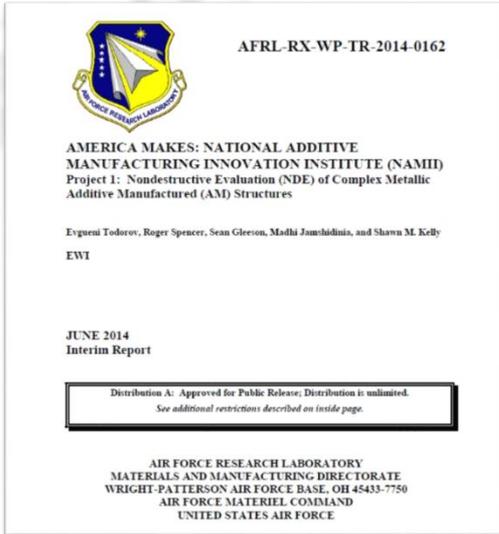
Effect of Design Complexity on NDE

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):



[§] 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



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



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.

