ASTM E07 Committee on Nondestructive Testing Activities

Jess Waller ♦ NASA WSTF

Steve James ♦ Aerojet Rocketdyne

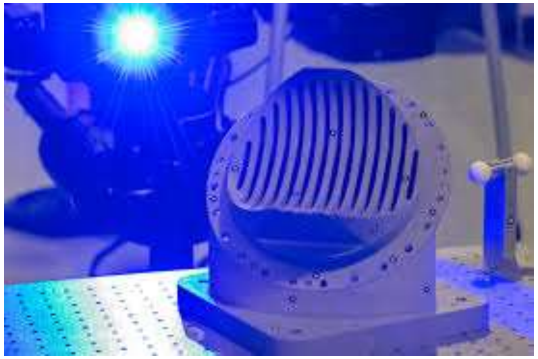
ASTM WK47031 draft Guide on NDT of AM Parts Used in Aerospace Applications
and Robin-Robin Testing

October 2015

NASA and non-NASA Players

- Nondestructive Testing has been identified as a universal need for all aspects of additive manufacturing
- U.S. government/industry/academia, together with our international colleagues, have an opportunity to push the envelope on ground and space-based additive manufacturing

NASA Agency & Prime Contractor Activity



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 fight testing

28-element Inconel 625 fuel injector

Prototype titanium to niobium gradient rocket nozzle

RL-10 engine thrust chamber assembly and injector

ISRU regolith structures

Made in Space AMF on ISS

Dynetics/Aerojet Rocketdyne F-1B gas generator injector

SpaceX SuperDraco combustion chamber for Dragon V2

Metallic Aerospace Components

GE Aviation will install 19 fuel nozzles into each Leading Edge Aviation Propulsion (LEAP) jet engine manufactured by CFM International, which is a joint venture between GE and France's Snecma. CFM has orders for 6000 LEAPs.

Lighter – the weight of these nozzles will be 25% lighter than its predecessor part.

Simpler design – reduced the number of brazes and welds from 25 to 5.

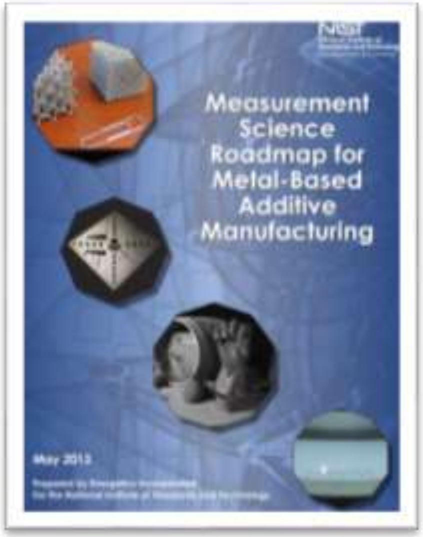
New design features – more intricate cooling pathways and support ligaments will result in 5X higher durability vs. conventional manufacturing.

"Today, post-build inspection procedures account for as much as 25 percent of the time required to produce an additively manufactured engine component," said Greg Morris, GE Aviation's business development leader for additive manufacturing. "By conducting those inspection procedures while the component is being built, (we) will expedite production rates for GE's additive manufactured engine components like the LEAP fuel nozzle."

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

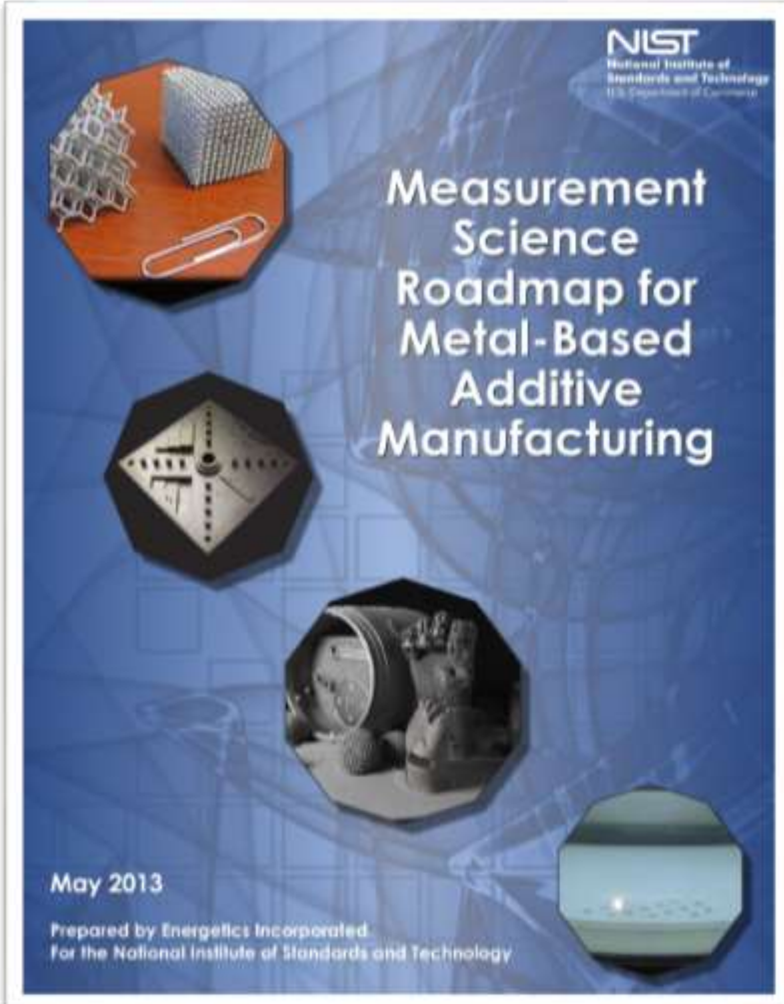
Background on ASTM E07.10 Subcommittee on Specialized NDT Methods NDT of AM effort

ASTM E07 Standard for NDT of AM Parts



ASTM Standard Guide for NDT of AM Parts Used in Aerospace Applications

NIST Roadmap TRL Gap Analysis



Contact: *Kevin Jurrens (NIST)*

- Technology challenges impede widespread adoption of AM
- Measurement and monitoring techniques, including NDT, cut across all aspects of AM, from input materials to processing to finished parts
- Ways to fully characterize AM parts, including NDT, 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

NIST Roadmap

Important Technology and Measurement Challenges for AM

AM Materials	AM Process and Equipment	AM Qualification and Certification	AM Modeling and Simulation
Characterization Data and Standards for Post Processing	NDE Techniques Optimized for Metals AM	Closed Loop Process Control	Expert System for AM Design
Robust In Situ Process Monitoring Techniques	Fast In-Situ Measurements	Standard Guidelines and Methods for Qualification and Certification	Validated Physics- and Properties-Based Models for AM
Metals Design Allowables Database	Performance Capability Database for AM Technologies	Shared/ Standardized Third-Party Data Repository	Standard Data Structures, Definitions, and Metrics for AM Models
	Sensors for Measuring and Monitoring AM Processes and Products	Standards and Protocols for Round-Robin Build and Material Testing	

- Cross-cutting needs for NDT and standards

NASA/TM-2014-218560 ♦ NDT of AM

NASA/TM—2014–218560

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

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White Sands Test Facility, Las Cruces, New Mexico

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November 2014

Industry, government and academia were asked to share their NDT of AM experience

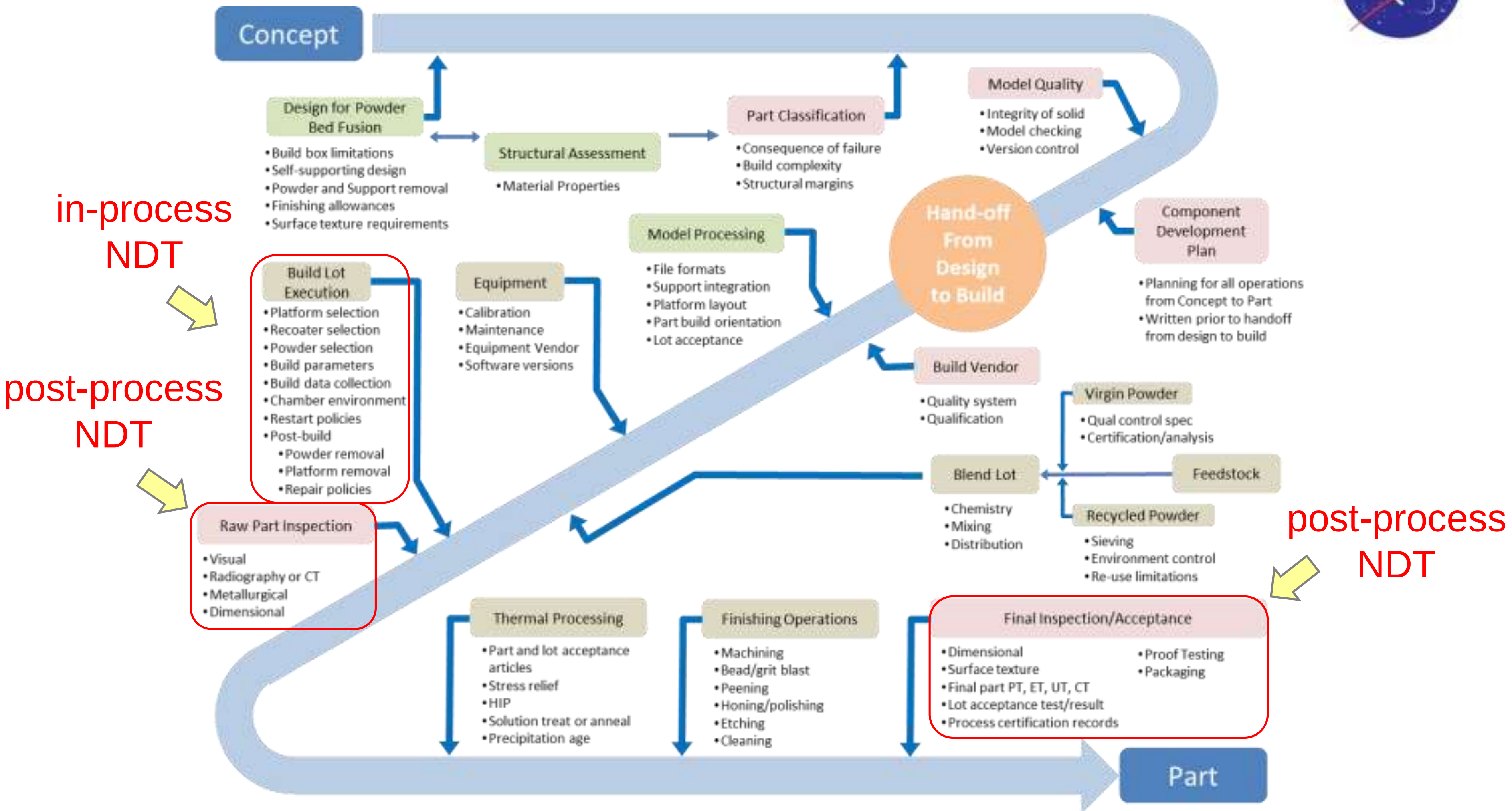
NDT Challenges

- Complex geometry (see AFRL-RX-WP-TR-2014-0162)
- As-built rough surface finish
- Variable and complex grain structure
- Undefined critical defect types, sizes and shapes
- Lack of effect-of-defect studies
- Lack of physical reference parts with AM defects
- Lack of written inspection procedures for AM processes
- Lack of probability of detection (POD) data
- Lack of mature in-process and post-process monitoring techniques

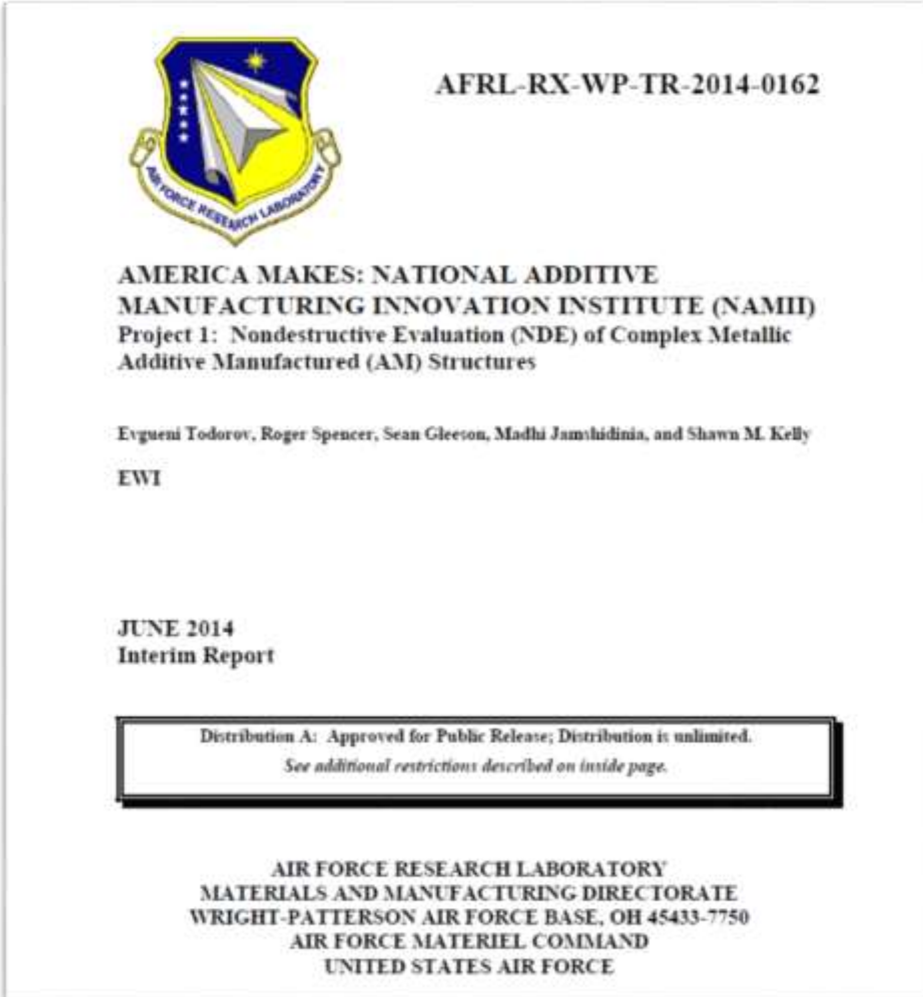
NDT Recommendations

- Develop ASTM E07-F42 standards for NDT of AM parts
- Develop in-process NDT to improve feedback control, maximize part quality and consistency, and obtain ready-for-use certified parts
- Develop post-process NDT of finished parts
- Apply NDT to understand effect-of-defect, and establish acceptance limits for certain defect types and defect sizes (FY16 NASA Foundational effort)
- Use NDT to understand scatter in design allowables database generation activities (process-structure-property correlation)
- Develop better physics-based process models using and corroborated by NDT
- Fabricate AM physical reference parts to demonstrate NDT capability
- Develop NDT-based qualification and certification protocols for flight hardware (screen of critical defects)

AM Part Qualification & Certification



AFRL-RX-WP-TR-2014-0162 ♦ NDT of AM



AFRL-RX-WP-TR-2014-0162

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

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

EWI

JUNE 2014
Interim Report

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See additional restrictions described on inside page.

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

Contact: *Evgueni Todorov (EWI)*

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

Complexity Groups

While most NDE techniques are applicable to complexity groups[§] 1 (Simple Tools and Components) and 2 (Optimized Standard Parts), and some to 3 (Embedded Features), only PCRT and CT are applicable to 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.

Complexity Groups ♦ NDT Selection

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

Qualification & Certification/NASA


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

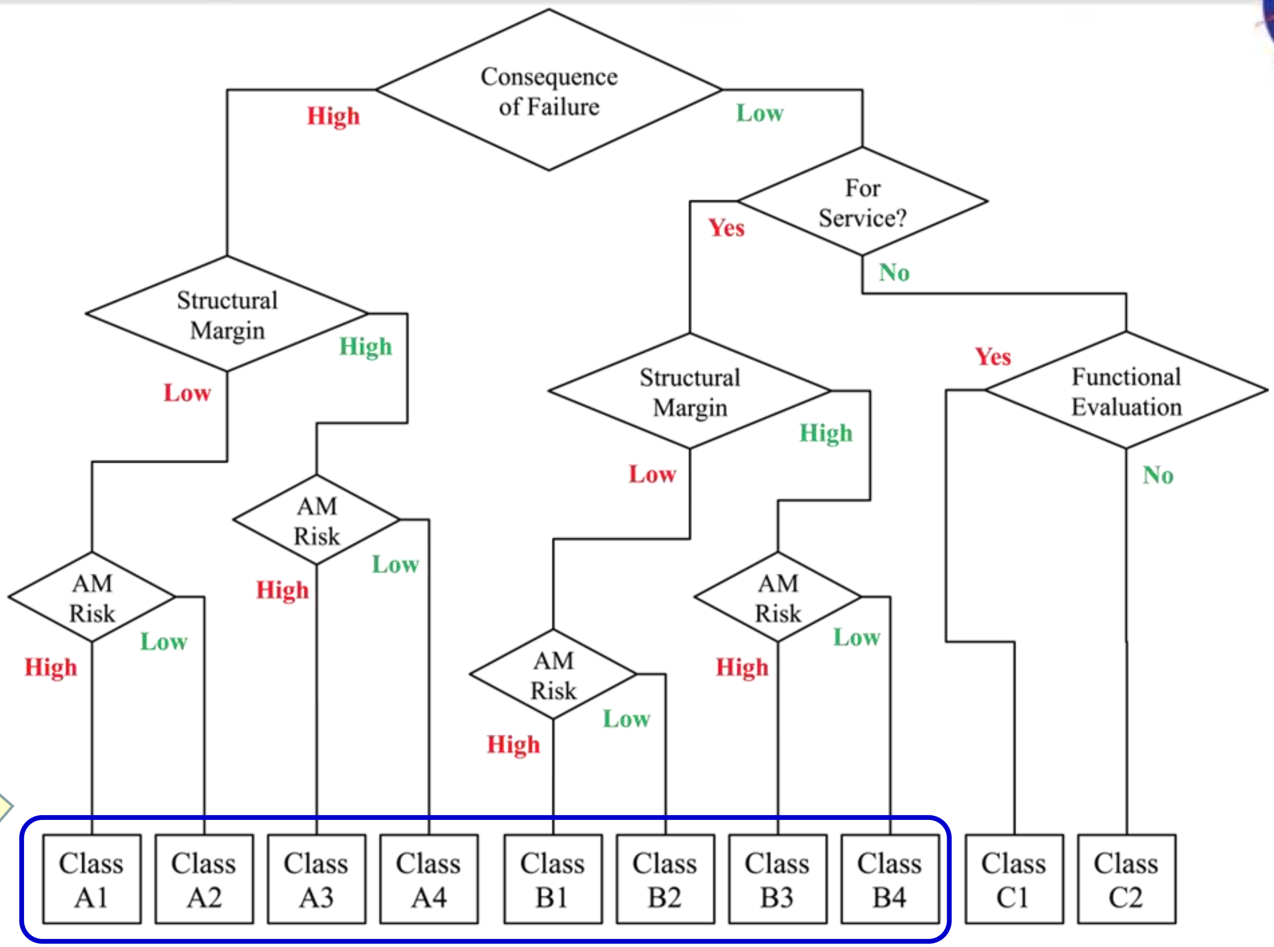
THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED

Contact: *Doug Wells (MSFC)*

- Comprehensive draft technical standard is in review
- All Class A and B parts are expected to receive comprehensive NDT 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
- NDT procedural details are still emerging

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

NASA AM Part Classification§



comprehensive NDT for surface and volumetric defects

§NASA classifications 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.

Spaceflight Hardware NDT Considerations

- 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 NDT.
- Knowledge of the CIFS for AM parts will allow the NDE and fracture control community to evaluate risks and communicate meaningful 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 NDT. To understand these risks it is important to identify the inaccessible region along with the CIFS.

Spaceflight Hardware NDT Considerations

- Parts with low AM risk should exhibit much greater coverage for reliable NDT.
- Multiple NDE techniques may be required to achieve full coverage.
- Surface inspection techniques (PT and ECT, but also 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 or abrasion, for example, require etching prior to inspection to remove smeared metal.
  Note: removal of the as-built AM surface merely to a level of visually smooth may be insufficient to reduce the NDE noise floor due to near-surface porosity and boundary artifacts.
- NDT demonstration parts with simulated CIFS defects are used to demonstrate NDT detection capability.
- NDE standard defect classes for welds and castings welding or casting defect quality standards will generally not be applicable for AM parts.

Spaceflight Hardware NDT Considerations

- 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 accepted AM defect catalog and associated NDE detection limits for AM defects is established, the NDE techniques and acceptance criteria remain part-specific point designs.

Qualification & Certification/USAF♦FAA

- Lack of qualification and certification procedures is an issue for NASA, USAF, FAA and commercial aerospace

U.S. AIR FORCE

Announcement: Government Workshop on Additive Manufacturing (for metals)

conducted in conjunction with the 2015 AA&S / P-SAR Conferences

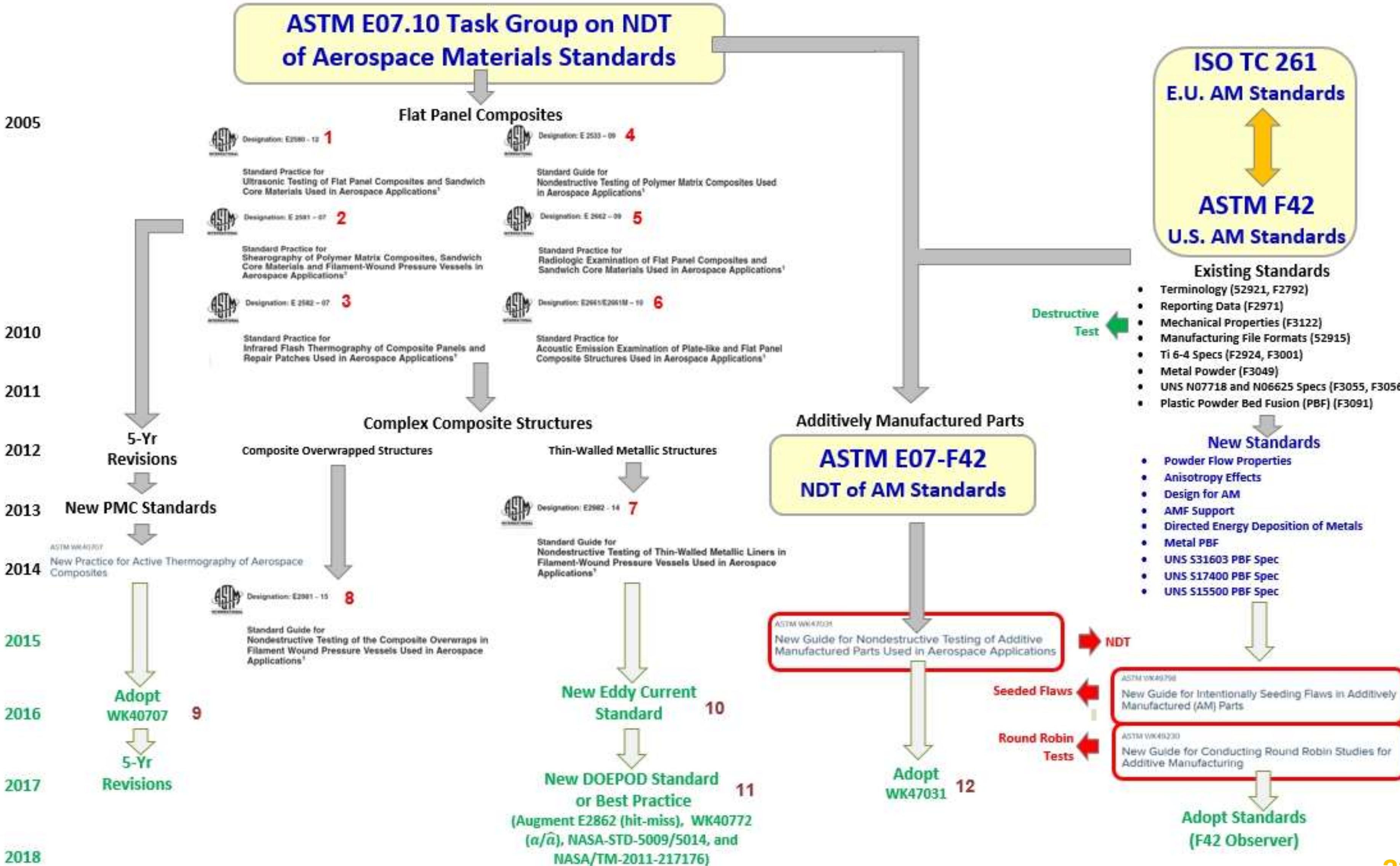
April 3, 2015

Location: The Baltimore Marriott Waterfront, Room Dover A/B

You are invited to attend the Government Workshop on Additive Manufacturing (for metals) that will take place on *Friday, April 3 2015 (8:00 am – 12:30 pm)* following the AA&S 2015 and P-SAR 2015 conferences in Baltimore, MD. *Attendance is limited to US government agencies*. The main focus of the Workshop will be on certification / qualification issues associated with AM components for Aerospace applications. Therefore, several agencies with certification and/or airworthiness responsibilities are invited to give their agency's "perspective" presentations that will be followed by a roundtable discussion. Workshop's scope / objectives and draft agenda are provided in the *Appendix* below.

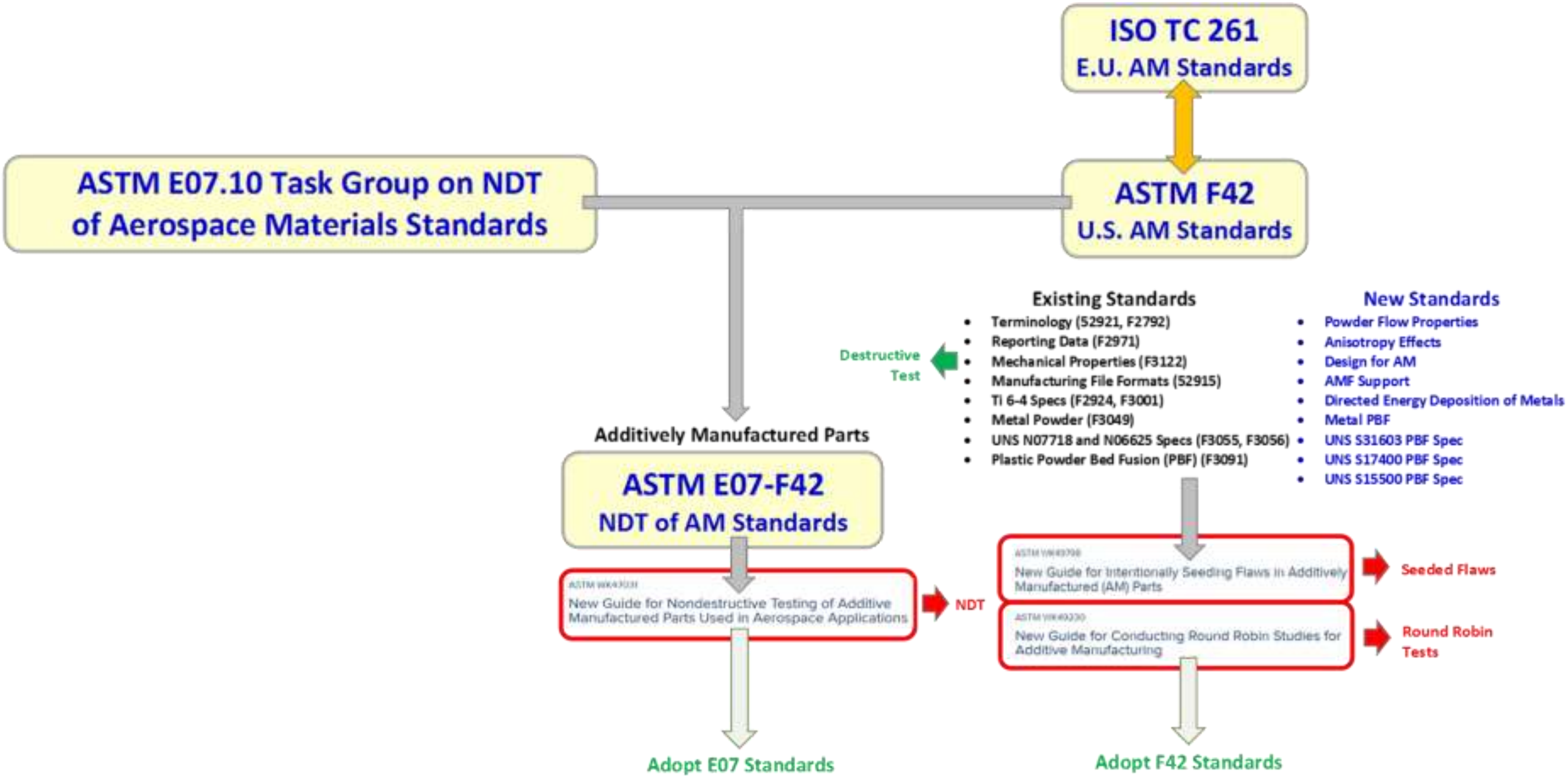
ASTM E07.10
Subcommittee on Specialized NDT Methods
Taskgroup on NDT of Aerospace Materials
NDT of AM effort

E07.10 TG on NDT of Aerospace Materials



ASTM E07-F42/ISO TC 261 Collaboration

NDT of Additively Manufactured Aerospace Parts



ASTM E07 Work Item WK47031

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ASTM WK47031

Work Item: ASTM WK47031 - New Guide for Nondestructive Testing of Additive Manufactured Metal Parts Used in Aerospace Applications

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

Go to Collaboration Area

MORE E07.10 STANDARDS | RELATED PRODUCTS | COPYRIGHT/PERMISSIONS

1. Scope

1.1 This Guide discussed the use of established and emerging nondestructive testing (NDT)procedures used during the life cycle of additive manufactured metal parts. 1.2 The parts covered by this Guide are used in aerospace applications; therefore, the inspection requirements for discontinuities and inspection points will in general be different and more stringent than for vessels used in non aerospace applications. 1.3 The metals under consideration include but are not limited to ones made from aluminum alloys, titanium alloys (Ti-6Al-4V), nickel-based alloys, cobalt-chromium alloys, and stainless steels. NOTE The combustion and ignition properties of finished part need to be taken into account for safe use in aerospace applications. 1.4 Protocols for controlling input materials, and established processes and post-process methods are cited whenever possible. The processes under consideration include but are not limited to Electron Beam Free From Fabrication (EBF3), electron beam melting (EBM), Direct Metal Laser Sintering (DMLS), and Selective Laser Melting (SLM). 1.5 This Guide does not establish or recommend procedures for NDT of additive manufactured metal parts made in space. 1.6 The Guide describes the application of established and emerging NDT procedures used during and after the additive manufacturing process; namely, Computed Tomography (CT, Section 7), Eddy Current Testing (ECT, Section 8), Infrared Thermography (IR, Section 9), Neutron Diffraction (Section 10), Penetrant Testing (PT, Section 11), Process Compensated Resonant Testing (PCRT, Section 12), Structured Light (SL, Section 13), and Ultrasonic Testing (UT, Section 14 including Phased Array Ultrasonic Testing (PAUT)). These procedures can be used by cognizant engineering organizations for detecting and evaluating flaws and defects during and after fabrication.. These procedures can be used by cognizant engineering organizations for detecting and evaluating flaws and defects during and after fabrication. 1.7 This Guide describes established practices that have a foundation in experience, and new practices that have yet to be validated. The latter are included to promote research and later elaboration in this Guide as methods of the former type. 1.8 This Guide does not specify accept-reject criteria to be used in procurement or used as a means for approving additively manufactured parts for service. Any acceptance criteria specified are given solely for purposes of refinement and further elaboration of the procedures described in this

Work Item Status

Date Initiated: 08-14-2014

Technical Contact: Jess Waller

Status: Draft Under Development

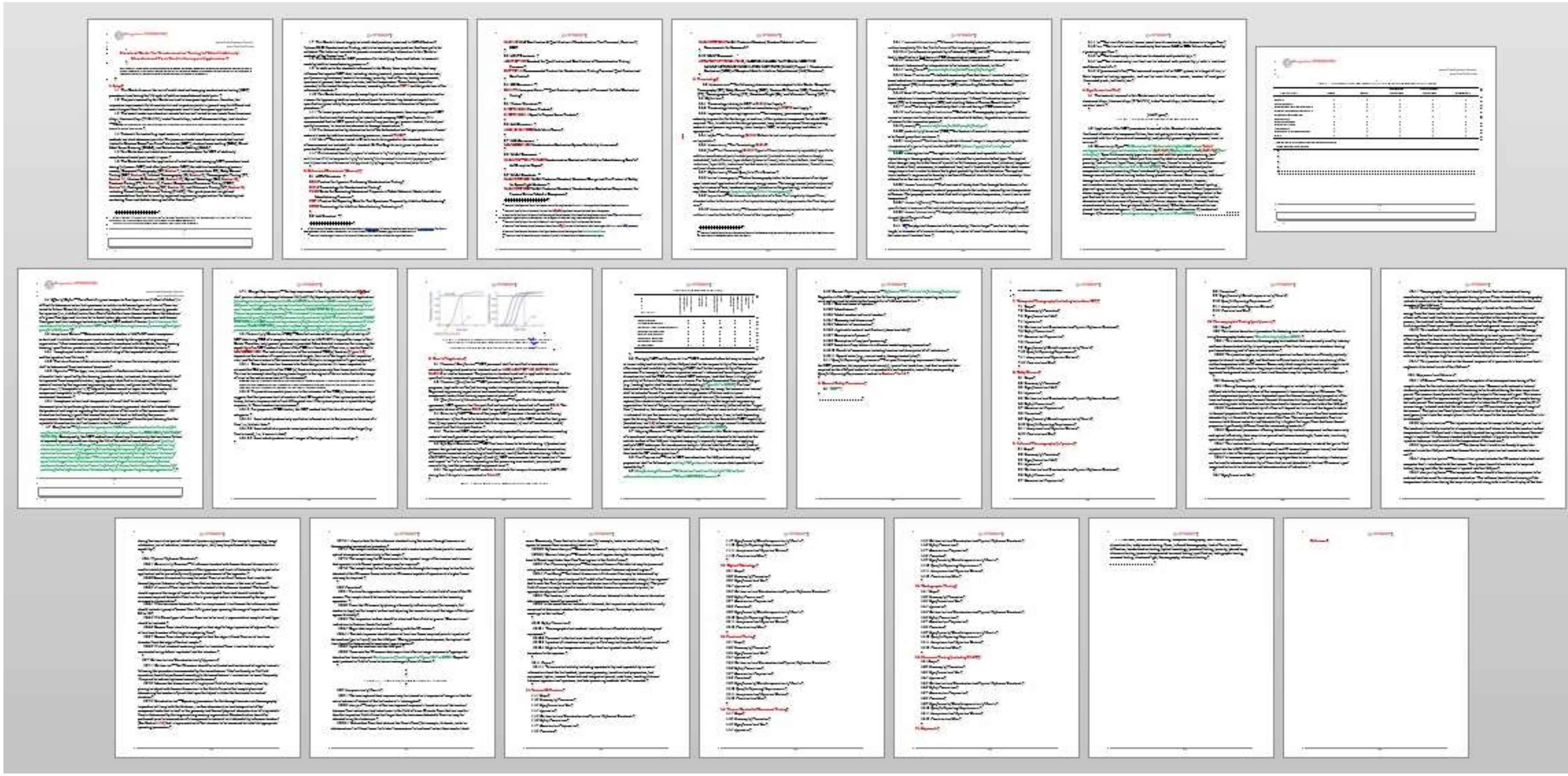
Recommended

2015 Committee Weeks in Anaheim

- Network with industry representatives
- No registration fee to attend for members and non-members.

https://myastm.astm.org

Current WK47031 NDE on AM Draft



Goal is to have a ready-for-ballot draft by the ASTM E07 January meeting

Current ASTM WK47031 Scope

1. Scope

1.1 This Guide discusses the use of established and emerging nondestructive testing (NDT) procedures used during the life cycle of additive manufactured metal parts.

1.2 The parts covered by this Guide are used in aerospace applications; therefore, the inspection requirements for discontinuities and inspection points in general may be different and more stringent than for materials and components used in non-aerospace applications.

1.3 The metals under consideration include but are not limited to ones made from aluminum alloys, titanium alloys (Ti-6Al-4V), nickel-based alloys, cobalt-chromium alloys, and stainless steels.

NOTE — The combustion and ignition properties of finished parts need to be taken into account for safe use in enriched oxygen aerospace applications.

1.4 Protocols for controlling input materials, and established processes and post-process methods are cited whenever possible. The processes under consideration include but are not limited to Electron Beam Free Form Fabrication (EBF^3), electron beam melting (EBM), Direct Metal Laser Sintering (DMLS), and Selective Laser Melting (SLM).

1.5 This Guide does not establish or recommend procedures for NDT of additively manufactured metal parts made in space.

NDT SMEs being sought

1.6 The Guide describes the application of established and emerging NDT procedures used during (in-process NDT) and after (post-process NDT) the additive manufacturing process; namely, Computed Tomography (CT, Section 7), Eddy Current Testing (ECT, Section 8), Infrared Thermography (IR, Section 9), Neutron Diffraction (Section 10), Penetrant Testing (PT, Section 11), Process Compensated Resonant Testing (PCRT, Section 12), Radiologic Testing (RT, Section 13), Structured Light (SL, Section 14), and Ultrasonic Testing (UT, Section 15, including Phased Array Ultrasonic Testing (PAUT)). This guide provides insight and recommendations that can be used by cognizant engineering organizations for detecting and evaluating flaws and defects during and after fabrication.

1.7 This Guide is based largely on established practices contained in ASTM Section 3 Volume 03.03 Nondestructive Testing, while also evaluating new practices that have yet to be

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NDE and AM equipment manufacturers, government agencies, academia, US and EU industry represented

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New members welcome, contact Jess Waller or Steve James!

WK47031 Section Writing Teams

Intro (Sections 1-5)

Leads: James and Waller *Collaborators*: Sinnema, Moylan

Defects (Section 4.3)

Lead: Dutton *Collaborators*: Walker

In-Process NDE

in-situ Infrared Thermography (IR, Section 7)

Lead: Moylan *Collaborators*: Middendorf, Vergara, Burke, Zalameda, Taminger

Post-Process NDE

Computed Tomography (CT, Section 8)

Lead: Hunter *Collaborators*: ASTM E07.01, Martin, Jones

Eddy Current Testing (ECT, Section 9)

Lead: TBD *Collaborators*: Todorov, ASTM E07.07

post-process Thermography (TT, Section 11)

Lead: Shepard *Collaborators*: TBD

Neutron Diffraction (Section 12)

Lead: Curtis-Rouse, *Collaborators*: Watkins, Farrell

Penetrant Testing (PT, Section 13)

Lead: Brausch *Collaborators*: TBD, ASTM E07.03

Process Compensated Resonance Testing (PCRT, Section 14)

Lead: Biedermann *Collaborators*: Hunter

Radiologic Testing (RT, Section 15)

Lead: LaCivita (interim) *Collaborators*: TBD, E07.01

Optical Metrology/Structured Light (OM, Section 16)

Lead: Waller *Collaborators*: MSFC, Wooliams, Cuypers

Ultrasonic Testing (UT, Section 17, includes PAUT)

Lead: James *Collaborators*: Koshti, Dutton, Djordjevic, ASTM E07.06

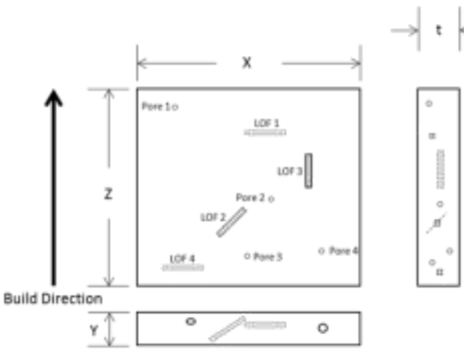
NDE Detection of Typical AM Defects

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

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

Conceptual WK47031 Round Robin Samples

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°

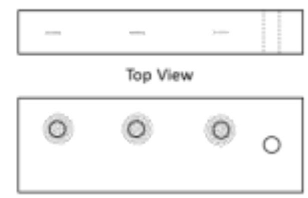
Artifact	Diameter
Pore 1	.5% of t
Pore 2	1% of t
Pore 3	1.5% of t
Pore 4	2% of t

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

ECT Sample

Side View

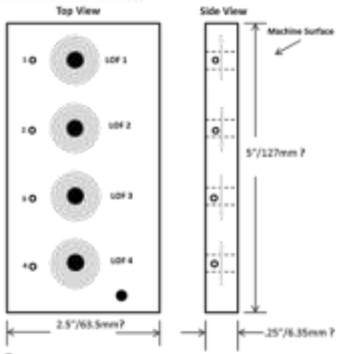
Top View



Lack of Fusion Vary % of t

Drilled Hole

Multiuse Sample (MUS)



Through Hole for ET .25"/6.35mm

FBH for UT

Pores 1 - 4

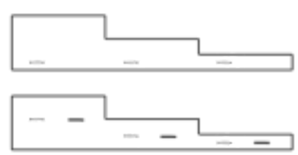
Area (.75"/19.05mm dia.) of Lack of Fusion for RT, UT, ET

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°

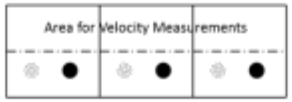
Artifact	Diameter
Pore 1	.5% of t
Pore 2	1% of t
Pore 3	1.5% of t
Pore 4	2% of t

UT Sample
Stepped vs. One Thickness

Side View

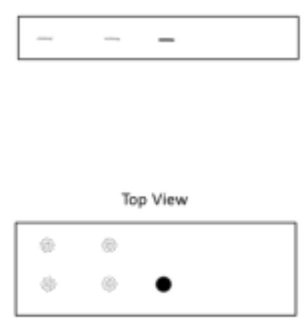


Top View



Side View

Top View



Lack of Fusion Vary % of t

Flat Bottom Hole

PT Sample
Fatigue Crack or Surface Texture

Side View

Top View

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).

Actual WK47031 Round Robin Samples

NASA LaRC EBF^3 samples

Ti 6-4 walls in "L" shape; shown part is 3 beads wide (~0.5" wall thickness)

3.5" OD copper tube with In625 deposited on the surface

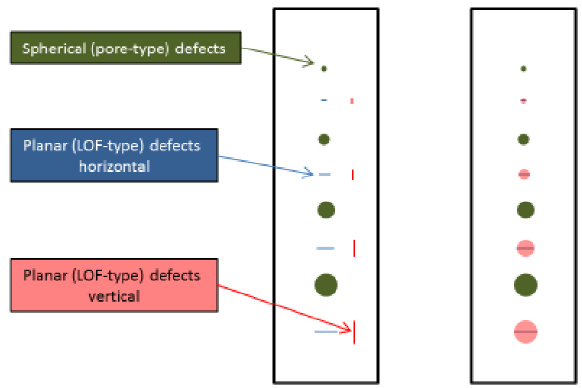
Cutaway of a 1.5" tall × 2-3.5 diameter (tapered) 316SS

2219 Al mixer, 2.5" diameter, ~0.75" high (available parts are just the bottom half of this part, below line shown in photo)

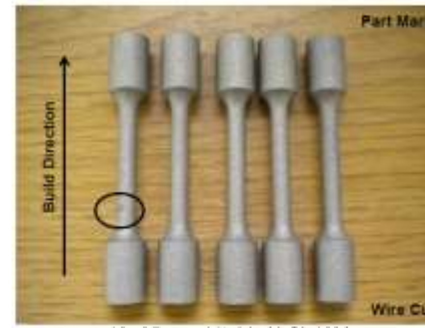
Georgia So. Univ. SLM samples§

10 × 70 mm (od × h) Ti 6-4 alloy cylindrical bars

ConceptLaser GmbH SLM samples (planned)



Airbus Laser PBF samples



13×85 mm (∅×h) Al-Si-10Mg dog bones (6 mm ∅×30 mm gauge)

MLPC, Inc. samples (planned)

Cylindrical bars for CT and PCRT evaluation

§Gong, H., Rafi, K., Guc, H., Janaki Ram, G. D., Starr, T., Stucker, B., *Influence of defects on mechanical properties of Ti–6Al–4V components produced by selective laser melting and electron beam melting, Matls and Design,* **86**, 545 (2015).

ASTM WK47031 Goals

- Capture current NDT of AM state-of-the-art in an ASTM Standard Guide
- Fabricate consistent parts using controlled materials and processes (F42), which are then distributed to various labs for a round-robin study.
- Assess the NDT capability of various labs to mature and refine NDT procedures and establish repeatability and reproducibility.
- Determine the detectability of seeded AM flaw types and sizes using down-selected, consensus NDT methods.
- Ultimately, generate Precision & Bias statements that can be used in accept-reject (i.e., an ASTM Test Method) and as a *means to qualify and certify AM flight hardware* used in aerospace applications.

Back-ups

NIST NDT of AM Effort

- Materials Standards for Additive Manufacturing propelled by a lack of confidence in consistent material properties of nominally identical metal powders and resulting AM parts
  - Finalizing WK40606 into ASTM Standard "*Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing*"
- Neutron Imaging to assess Thermal Stress
  - The extremely rapid and localized melting and cooling results in residual thermal stresses
  - Interest in residual thermal stresses present after a build, as well as the effects of post-processing (shot-peening, heat treatments) and part removal on stress
  - Working with both ORNL and NCNR for neutron imaging of stress (complimentary capabilities)
- Ultrasonic Porosity Sensor: Process Monitoring
- Z-Axis Interferometer Measurements

AM Risk

Class A, B and C subclasses arise depending on AM Risk , which accounts AM risk accounts for part inspection feasibility and AM build sensitivities:

Criteria to Evaluate Additive Manufacturing Risk

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	

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

- ⇨ Optical Method (OM)
- ⇨ parts where liquid/gas leak tightness reqd.
- ⇨ post-machining reqd., line of sight issues
- ⇨ ASTM E2534
- ⇨ correlate R, σ with mechanical props
- ⇨ correlate σ with microstructure and residual stresses
- ⇨ measurement of compressive elastic stresses by peening

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

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

Qualification & Certification/NASA

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

Certification process has two parts:

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

As-built Hardware Certification:
Hardware certification occurs throughout the life-cycle of the hardware to ensure fabricated hardware fully meets the intent of the certified design definition at the time of flight. All hardware in the flight system will have verification of compliance leading to final Certification of Flight Readiness (CoFR).

ASTM E07 Committee on NDT

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Staff Manager: Kathleen McClung 610-832-9717

ASTM Committee E07 on Nondestructive Testing was formed in 1938. E07 meets twice a year, in January and June, with approximately 100 members attending four days of technical meetings and concludes on the fifth day with a plenary session of the Main Committee. The Committee, with a membership of over 400, currently has jurisdiction of over 175 standards, published in October in the Annual Book of ASTM Standards; Volume 03.03. E07 has 12 technical subcommittees that maintain jurisdiction over these standards. Information on this subcommittee structure and E07's portfolio of approved standards and Work Items under development are available from the List of Subcommittees, Standards and Work Items below. These standards have, and continue to play, a preeminent role in all aspects relating to traditional and emerging methodologies for Radiology (X, Gamma and Neutron), Liquid Penetrant, Magnetic Particle, Acoustic Emission, Ultrasonics, Electromagnetics, Leak Testing, and Reference Radiological Images.

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Committee F42 on Additive Manufacturing Technologies

Staff Manager: Pat Picariello 610-832-9720

ASTM Committee F42 on Additive Manufacturing Technologies was formed in 2009. F42 meets twice a year, usually in January and July, with about 70 members attending two days of technical meetings. The Committee, with a current membership of approximately 215, has 4 technical subcommittees; all standards developed by F42 are published in the Annual Book of ASTM Standards, Volume 10.04 . Information on the F42 subcommittee structure, portfolio of approved standards, and Work Items under development, is available from the List of Subcommittees, Standards and Work Items below. These standards will play a preeminent role in all aspects of additive manufacturing technologies.

ASTM Committee F42 on Additive Ma

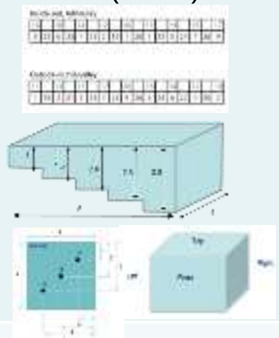
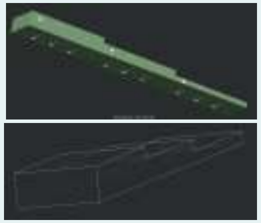
0:00 / 4:21

See all ASTM Intl. videos at YouTube

WK47031 Section Writing Teams

Industry Group Members & Affiliation	Affiliation	General NDE interest	Intro	Defects	CT	PCRT	ND	UT/ PAUT	OM/ MET	IR	ECT	RT	PT	TT	General AM interest	AM Process Equip.
Eric Biedermann, Vibrant Technologies Inc.	Industry, Vibrant					X										
Eric Burke, NASA LaRC	NASA-LaRC									X						
Charles Buynak	USAF														X	
V. Carl	EU									X						
Damaso Carreon, US Air Force Tinker AFB	USAF				X											
Mike Curtis-Rouse, SS Electron Powder Bed	EU				X		X									X
Boro Djordjevic	NESC NDE TDT							X								
Andre Droese	EU, Airbus	X														
Ben Dutton	ISO TC 261	X		X	X			X			X				X	
Jim Engel, Boeing	Industry, Boeing							X				X	X			
Shannon P. Farrell, Ph.D.	ISO TC 261						X									
Jennifer Fielding	USAF														X	
Joe Gabris, Boeing	Industry, Boeing							X				X	X			
Ed Generazio, NASA LaRC	NASA-LaRC	X														
Ed Ginzel, Consultant	consultant							X								
Amy Glover	EU				X								X			
Lem Hunter, Vibrant Technologies Inc.	Industry, Vibrant				X	X										
Steve James, Aerojet Rocketdyne	Industry, AEROJ							X								
Griffin Jones	EDU				X											
Justin Jones, NASA GSFC	NASA-GSFC				X											
Kevin Klug, WK49798 Seeded AM Flaws POC	Industry, CTC	X	X													
Ajay Kosti, NASA JSC	NASA-JSC				X			X								
Eric Lindgren	USAF	X	X													
Blake Marshall	DOE														X	
Rich Martukanitz	EDU				X											
Rich Martin, NASA GRC	NASA-GRC				X			X					X			
Shawn Moylan, NIST, WK49230 AM Round Robin Test POC	NIST														X	X
Charles Nichols, NASA WSTF	NASA-WSTF	X	X													
Dr. Germán Vergara Ogando	EU, NIT									X						
Arturo Baldasano Ramirez	EU, NIT									X						
Jerome Rownd, LMCO	Industry, LMCO							X								
Scott Roberts, NASA JPL	NASA-JPL				X			X								
Michael Ruddy, ASTM E07.06 Chair	ASTM E07							X								
Regor Saulsberry, NASA WSTF	NASA-WSTF	X	X													
Steve Shepard, Thermal Wave	Industry, Thermal Wave													X		
Gerben Sinnema	ESA	X	X													
Surendra Singh, Honeywell	Industry, Honeywell					X		X				X	X			
John Slotwinski, F42.01 Test Methods Chair	EDU		X					X							X	
Thomas L. Starr	EDU									X						
Richard Stiff, Aerojet Rocketdyne	Industry, AEROJ											X	X			
Karen Taminger, NASA LaRC, Ti EBF3 parts	NASA-LaRC															X
LaNetra Tate, NASA STMD	NASA-STMD		X												X	
Evgueni Todorov, EWI	Industry, EWI	X	X					X			X					
James Walker, NASA MSFC, NASA NDE AM WG Lead	NASA-MSFC	X			X				X		X				X	
Jess Waller, NASA, ASTM WK 47031 Leader	NASA-WSTF	X	X												X	
Mark Warchol	contract research							X								
Andrew Washabaugh, ASTM, MIT	ASTM E07										X					
Thomas Watkins	DOE						X									
Wim Cuypers	EU								X							
Peter Woolliams, , SS Electron Powder Bed	ISO TC 261				X				X							X
Joseph Zalameda, NASA LaRC	NASA-LaRC									X						

Actual NASA Physical Reference Samples

	MSFC-GRC	GSFC	LaRC	JSC-LaRC	KSC
AM process method	DMLS	DMLS (metal), LS (plastic)	LS	EBF³	EBM
alloys	titanium, Inconel, and aluminum	titanium, SS PH1, vero-white RGD835	SS	titanium	titanium
reference standard geometries			Conventional:  AM (planned): 	wrought (JSC) and AM (LaRC): 	2nd iteration (AM):  future (AM): 
features interrogated	complex geometries; large/thick/dense and very thin cross sections; (universal NDE standard, slabs, rods, gage blocks)	rectangular prisms, rows of cylinders, cylinders, flat-bottom holes, cone	steps, flat bottom holes	bead arrays, steps, holes	36 printed in-holes beginning at surface; 9 printed in-spheres internal to the part; cold plate (future)
AM defects interrogated	porosity/unfused matl. (restart, skipped layers), cracks, FOD, geometric irregularities	hole roughness and flatness/centricity	porosity, lack of fusion	grain structure, natural flaws, residual stress, microstructure variation with EBF³ 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

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