TRISMAC 2015 Trilateral FTF

Qualification of Products Fabricated via Additive Manufacturing Using Nondestructive Evaluation

May 21, 2015

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ESA-ESRIN Frascati, Italy

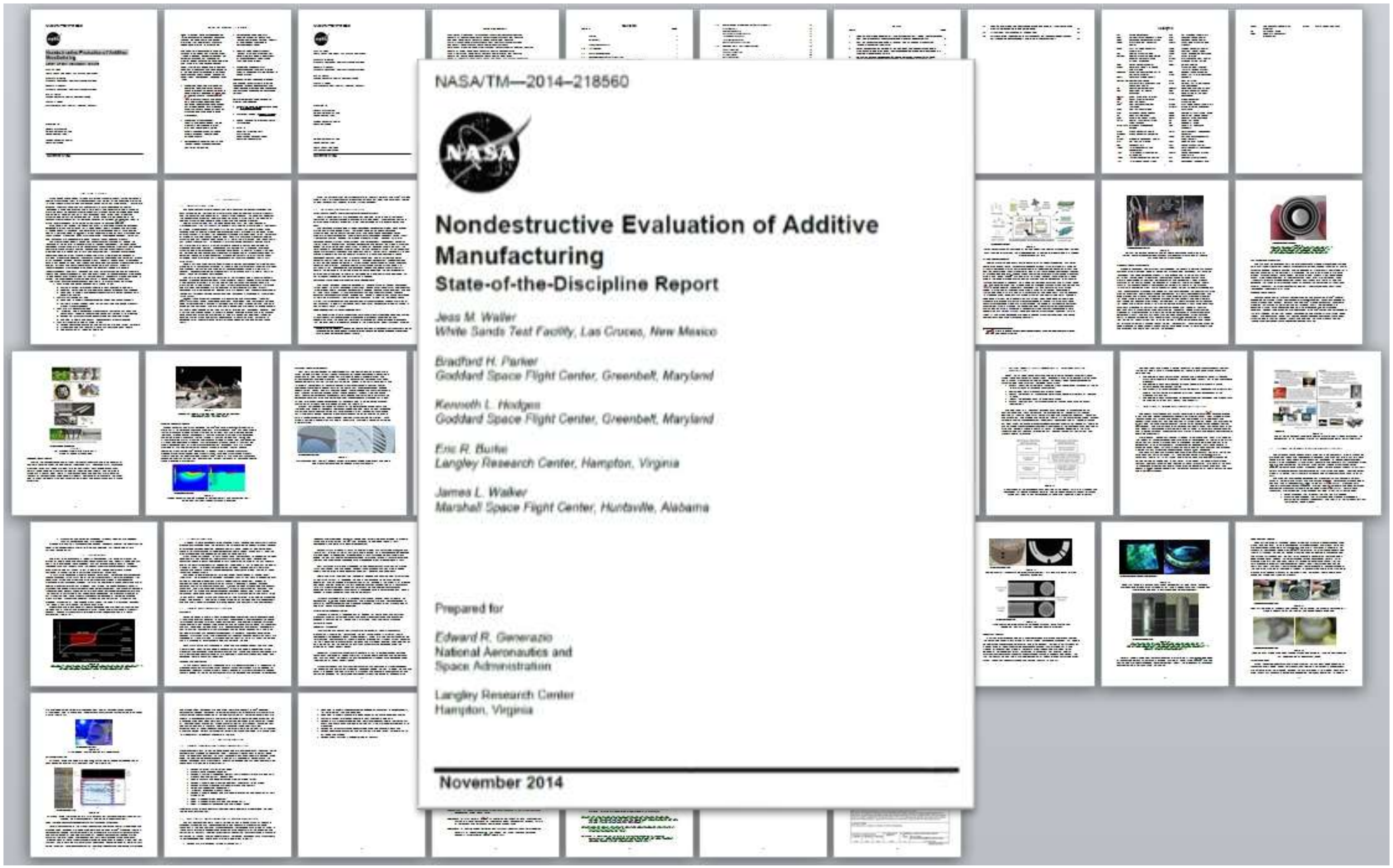
Virtual 16:10:00-16:25:00

NASA and non-NASA Players: NDE of Additive Manufacturing

- Workshops and technical interchange meetings attended by NASA have identified NDE as a universal need for all aspects of additive manufacturing.

- NASA/ESA/JAXA have an opportunity to push the envelope on **ground-based** manufacturing of lightweight design-to-constraint parts, and **space-based** manufacturing of flight spares and replacement hardware crucial for long-duration missions.

NASA/TM-2014-218560
NDE of AM State-of-the-Discipline Report



Industry, government and academia have been actively solicited to share their NDE experience relative to additive manufacturing

NASA/TM-2014-218560

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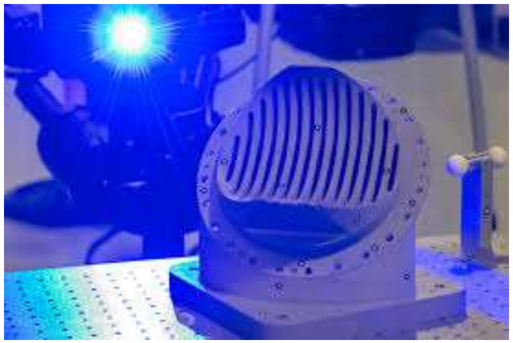
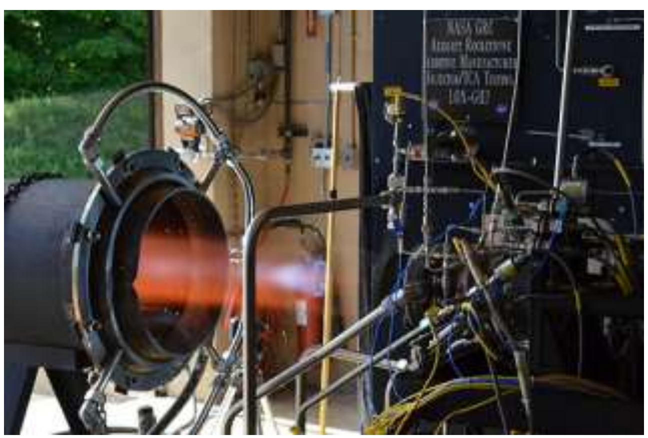
NASA Agency Activity



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

Reentrant titanium tube made by AM for a cryogenic thermal switch for the ASTRO-H Adiabatic Demagnetization Refrigerator

EBF3 system during parabolic fight testing



Hot-fire testing of RL-10 engine copper alloy thrust chamber assembly and injector

Prototype titanium to niobium gradient rocket nozzle

Metallic Aerospace Components

NASA's rocket injectors manufactured with traditional processes would take more than a year to make, but with these new 3D printing processes, the parts can be produced in less than four months, with a **70 percent reduction in cost**.

28 element Inconel 625 fuel injector built using SLM process

Using traditional manufacturing methods, **163 individual parts would be made and then assembled. But with 3-D printing technology, only two parts were required**, saving time and money and allowing engineers to build parts that enhance rocket engine performance and are less prone to failure.

Metallic Aerospace Components

“Through 3D printing, robust and high-performing engine parts can be created at a fraction of the cost and time of traditional manufacturing methods,”

“It’s a very complex engine, and it was very difficult to form all the cooling channels, the injector head, and the throttling mechanism. Being able to print very high strength advanced alloys ... was crucial to being able to create the SuperDraco engine as it is.” said Elon Musk.[1]

Compared with a traditionally cast part, the strength, ductility, fracture resistance, and variability in materials properties of a printed part must be verified and validated.

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

[1] http://www.newspacejournal.com/2014/05/30/spacex-unveils-its-21st-century-spaceship/

Metallic Aerospace Components

GE 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 in weight – 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.

NDE Challenges

- Complex geometry
- 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 standards
- Lack of written inspection procedures for AM processes
- Lack of probability of detection (POD) data
- Lack of mature In process monitoring techniques

NDE Recommendations

- Develop ASTM E07-F42 standards for NDT of AM parts
- Develop in-process NDT to improve feedback control, to maximize part quality and consistency, and to obtain certified parts that are ready-for-use directly after processing
- 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
- Fabricate physical reference standards to verify/validate NDT data
- Apply NDT to understand scatter in design allowables database generation activities
- Develop better physics-based process models using and corroborated by NDT
- Develop NDT-based qualification and certification protocols for flight hardware that rely on testing and modeling

NASA OSMA Publicity of NDE of AM Effort

https://sma.nasa.gov/news/news/2015/03/04/nasa-explores-nde-options-for-evaluating-additively-manufactured-parts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NASA Explores NDE Options for Evaluating Additively Manufactured Parts
Mar 04, 2015

SMA Leadership Profile: Greg Blaney
Mar 02, 2015

SMA Discussion Forum: Counterfeit Parts Avoidance, Part II
Feb 18, 2015

NASA Explores NDE Options for Evaluating Additively Manufactured Parts
Mar 04, 2015

Although Additive Manufacturing (AM) has been around for decades, increasing awareness of the significant benefits of flying 3D printed parts and using 3D printers in space has pushed NASA and the aerospace industry to take a close look at how to evaluate and certify AM parts to assure safety and mission success.

"[With 3D printing], you can print an entire part," explained LaNetra Tate, principal investigator for NASA's Space Technology Mission Directorate. "With traditional methods you can build, inspect, build, inspect, but with 3D printing, you're doing it in one swoop. We need to understand how we are going to verify and qualify and certify these parts."

AM has the potential to produce lighter parts, enhance the strength and reliability of materials, create less waste, reduce up-mass, and ultimately result in cost savings. However, there is a significant challenge in utilizing these promising parts — the most readily performed methods for evaluating 3D printed parts are

Certification (Doug Wells)

Doug Wells at MSFC has put together several sets of charts on the Certification process for Powder Bed Fusion AM Parts, the following information is from Doug's presentations.

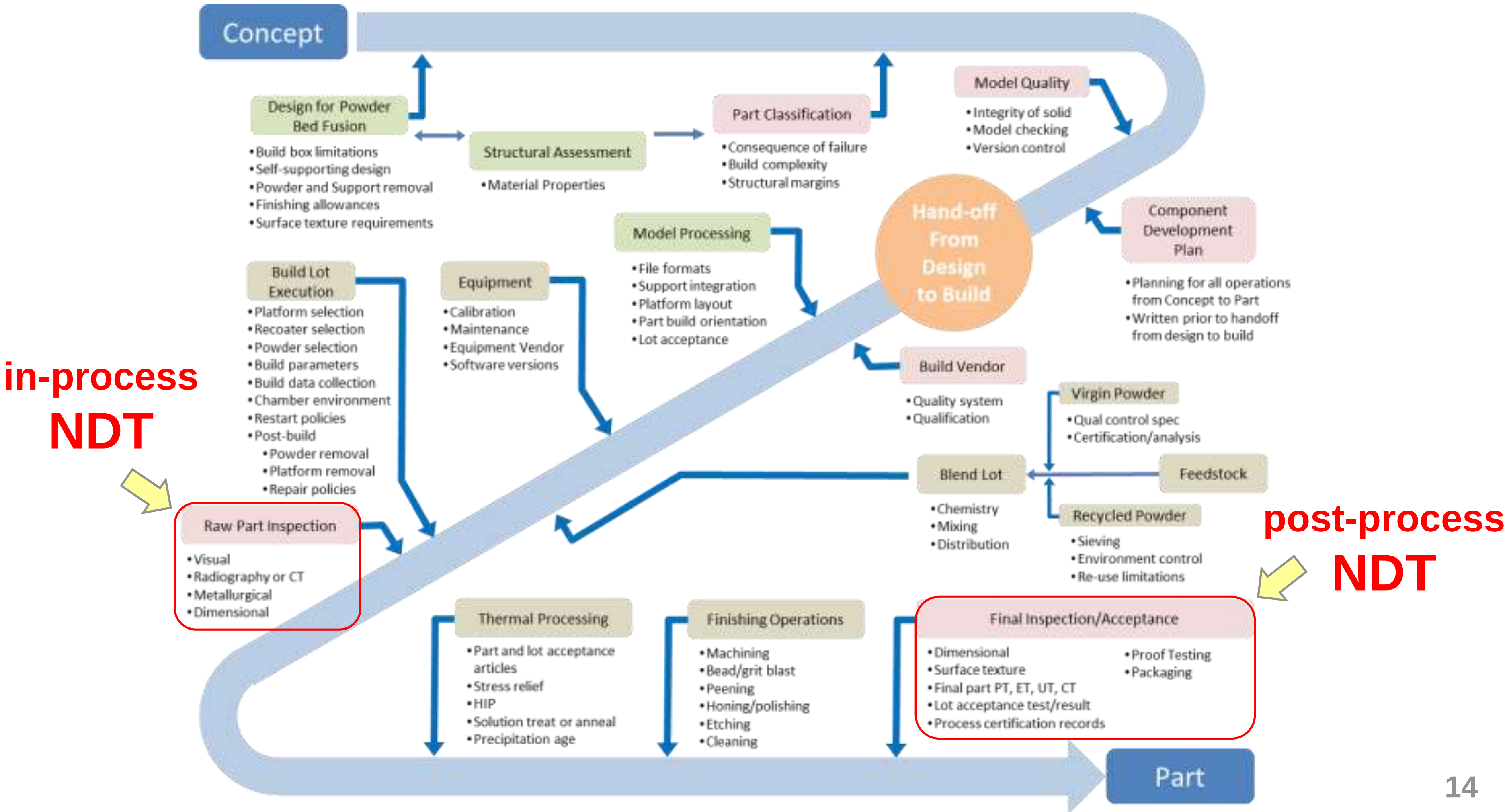
Certification is the affirmation by the program, project, or other reviewing authority that the verification and validation process is complete and has adequately assured the design and as-built hardware meet the established requirements to safely and reliably complete the intended mission.

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).

Certification



Qualification and Certification

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.

Organized by Rollie Dutton of the U.S. Air Force and Michael Gorelik of the FAA

Qualification and Certification

Technical Exchange on
Coordination of Standards Development for Additive Manufacturing

October 7th and 8th, 2015

University Park, PA

Wednesday, October 7th

Session I: Opening Session with Presentations from Standards Organizations

General Assembly with All Participants:

1:00	Welcome and Introductory Remarks
1:10	ASTM Presentation with Discussion
1:50	SAE Presentation with Discussion
2:30	Break
3:00	ASME Presentation with Discussion
3:40	AWS Presentation with Discussion
4:20	ISO Presentation with Discussion
5:00	Adjourn Session I

Evening Reception and Networking Event

Thursday, October 8th

Session II: Presentations from User Perspectives

General Assembly with All Participants:

8:00	Presentation on Industry Perspective on Needs for Standards and Discussion
8:40	Presentation on NIST Perspective on Needs for Standards and Discussion
9:20	Presentation on Government Perspective of Needs for Standards and Discussion
10:00	Break
10:30	Presentation on Concepts for Performance Qualification and Discussion
11:10	Presentation on Material Property Data Bases and Discussion
11:50	Objective and Guidelines for Collaborative Session
12:00	Adjourn Session II

Collaboration Group A:

1:00 Dialogue on Coordination of U.S. Standards

Collaboration Group B:

1:00 Dialogue on Qualification and Certification

Session IV: Summaries and Discussion

General Summaries with All Participants:

3:30	Summary of Collaboration Group A and Discussion
4:15	Summary of Collaboration Group B and Discussion
5:00	Adjourn Technology Exchange

Organized by Shane Collins of Incodema and Rich Martukanitz at PSU CIMP 3D

ASTM E07 Committee on Nondestructive Testing

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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

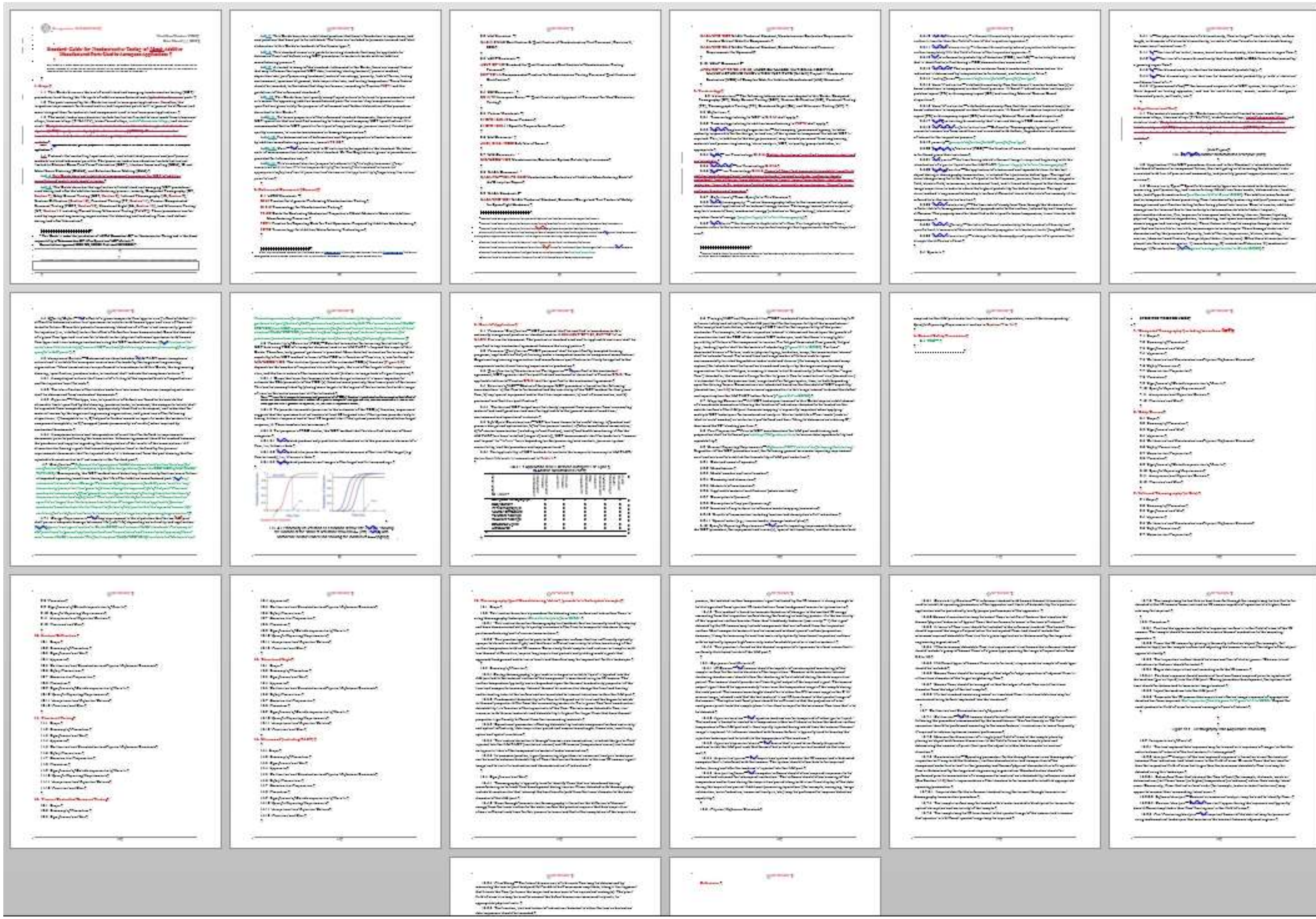
Recommended

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



Currently assembling writing teams of NDE SMEs

Current ASTM WK47031 Scope

NDT SMEs being sought

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.

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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Approach: Incorporate U.S. Air Force Expertise and Findings

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
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UNITED STATES AIR FORCE

Evgueni Todorov, et al., did a superb job on an initial handling of NDE and AM.

Document has a ranking system based on complexity to direct NDE of AM efforts.

Early results on NDE application to AM are documented.

Approach for future work based on CT and PCRT.

Approach: Incorporate U.S. Air Force Expertise and Findings

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 xCT would be applicable to Groups 4 (Design to Constraint Parts) and 5 (Free-Form Lattice Structures):

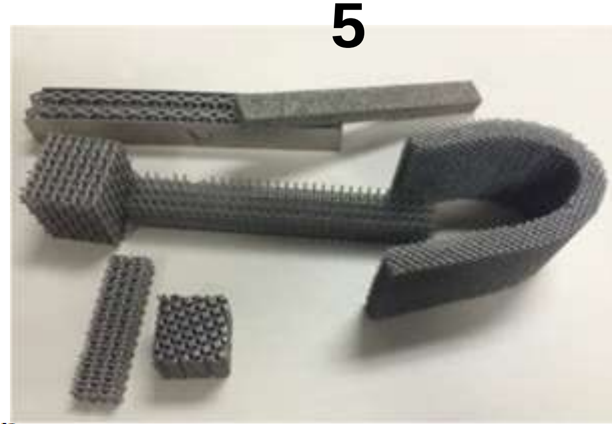
1

2

3

4

5



§ O. Kerbrat, P. Mognol, J.Y. Hascoet, "Manufacturing Complexity Evaluation for Additive and Subtractive Processes: Application to Hybrid Modular Tooling", IRCCyN (Institut de Recherche en Communications et Cybernétique de Nantes), MO2P Team1 rue de la Noë, BP 92101, 44321, Nantes Cedex 03, France., pp 519-530, September 10, 2008

Approach: Incorporate U.S. Air Force Expertise and Findings

Application of NDE techniques to complexity Groups 1-5

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

Approach: Incorporate BSI Expertise (A. Price)

Table 1: NDT method					
In-process:	Ultrasonic	Infrared	Visual inspection	Thermal cameras	
Post-process:	Ultrasonic	X-ray	Vibro-acoustic	3D x-ray CT	Process Compensated Resonance Testing

Table 2: NDT standards
Ultrasonic
BS EN 1330-4:2010. Non-destructive testing. Terminology Terms used in ultrasonic testing
BS EN ISO 16810:2014. Non-destructive testing. Ultrasonic testing. General principles
BS EN ISO 16827:2014. Non-destructive testing. Ultrasonic testing. Characterization and sizing of discontinuities
Infrared
BS ISO 10878:2013. Non-destructive testing. Infrared thermography. Vocabulary
Visual Inspection
BS ISO 3058:1998. Non-destructive testing. Aids to visual inspection. Selection of low-power magnifiers
BS 7910:2013. Guide to methods for assessing the acceptability of flaws in metallic structures
Thermal cameras
No standards found
X-ray
BS EN 12543-1:1999. Non-destructive testing. Characteristics of focal spots in industrial X-ray systems for use in non-destructive testing Scanning method
Vibro-acoustic
BS EN ISO 10846-1:2008. Acoustics and vibration. Laboratory measurement of vibro-acoustic transfer properties of resilient elements Principles and guidelines
3D x-ray CT
ASTM E2767 - 13. Standard Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE) for X-ray Computed Tomography (CT) Test Methods
Process Compensated Resonance Testing
ASTM E2534 - 10. Standard Practice for Process Compensated Resonance Testing Via Swept Sine Input for Metallic and Non-Metallic Parts

Courtesy of Alex Price

Lead Programme Manager

bsi.

"UK side happy to collaborate"

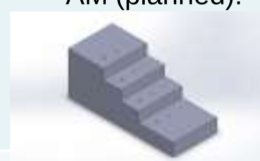
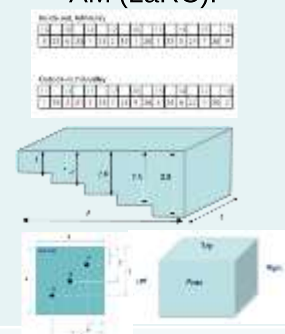
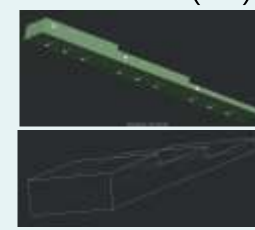
(B. Dutton)

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/

NASA
Physical Reference Standards

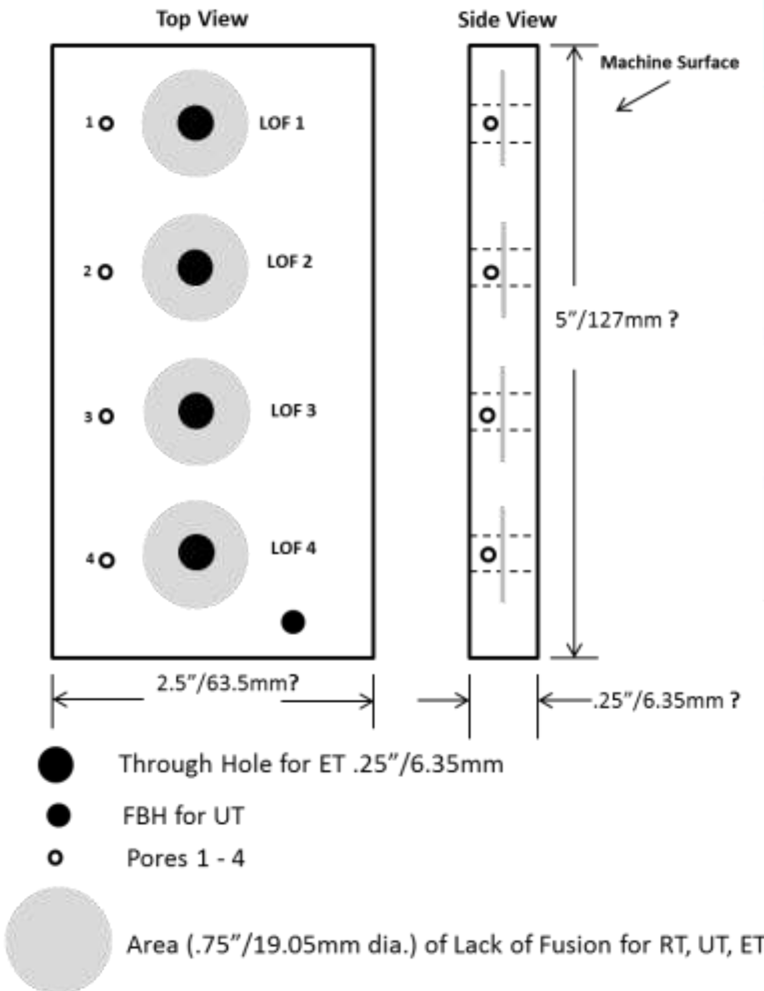
	MSFC-GRC	GSFC	LaRC	JSC-LaRC	KSC
AM process method	DMLS	DMLS (metal), LS (plastic)	LS	EBF^3	EBM
alloys	titanium, Inconel, and aluminum	titanium, SS PH1, vero-white RGD835	SS	titanium	titanium
reference standard geometries			Conventional:  AM (planned): 	wrought (JSC) and AM (LaRC): 	2nd iteration (AM):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

WK47031 Round-Robin Test Physical Reference Standards (S. James)

Proposed ASTM F42.01 standard:

Standard Guide for Determining Non-Destructive Inspection (NDI) Detection Limits for Additively Manufactured (AM) Parts Via Intentional Seeding Of Defects

Multi Use 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

WK47031 Round Robin Test Goal

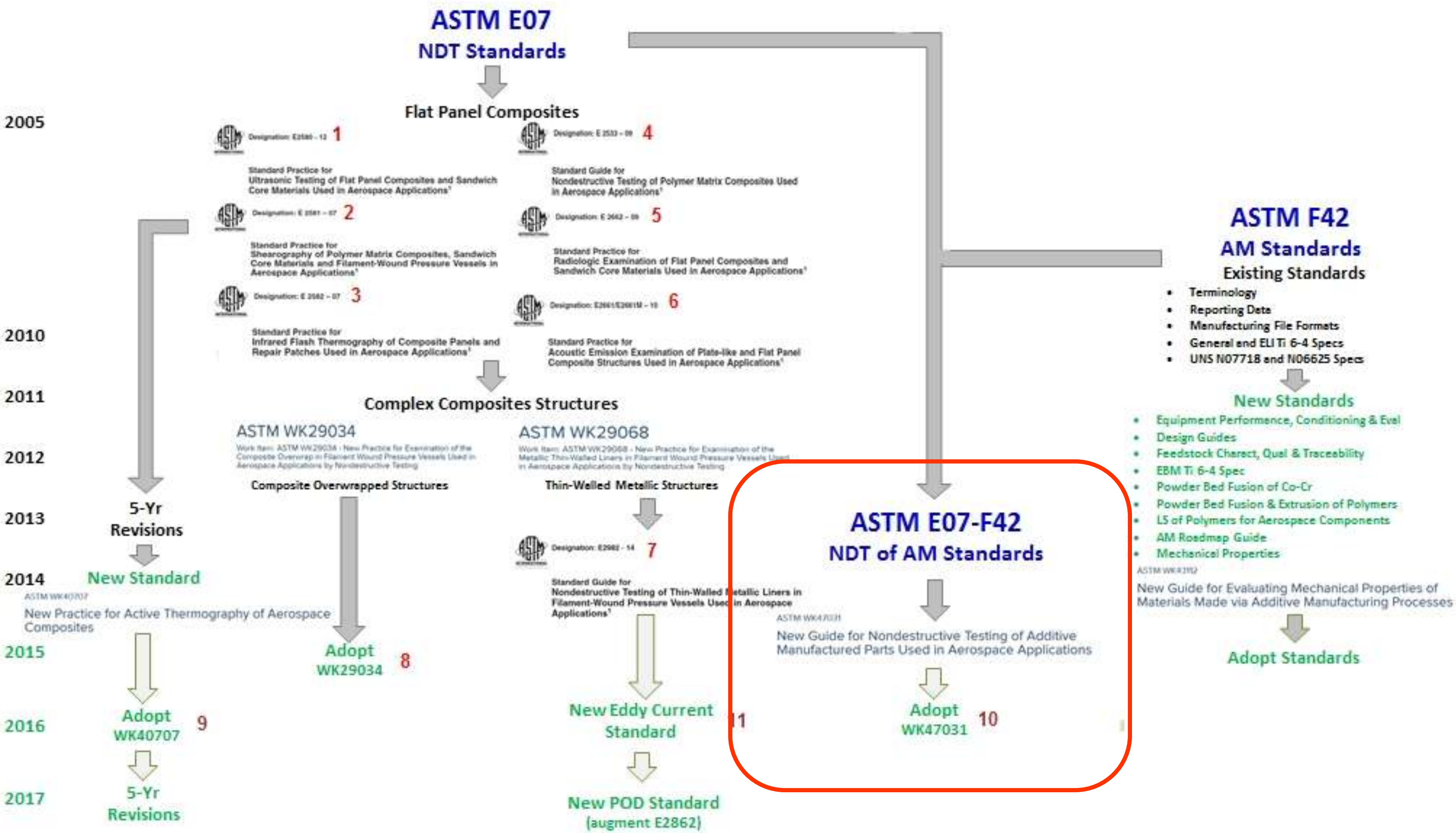
- The goal is to fabricate consistent parts using controlled materials and processes (F42), which are then distributed to various labs for a round-robin study.
- The NDE capability of the various labs is assessed internally and compared to external labs to establish both repeatability and reproducibility.
- The detectability of intentionally added AM flaws type ands sizes is then evaluated for down-selected consensus NDE methods.
- Ultimately, the goal is to determine repeatability and reproducibility, 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 space applications.

Back-up

Gap Analysis: NDE's Role

- Lack of design allowables. NDE should be performed on test specimens to help correlate data scatter to build variability (effect of defects).
- Lack of in-process NDE. IR thermal imaging of melt zone and high speed visual imaging to validate defect free fabrication process.
- Development of post processing protocols. Before and after NDE to confirm effectiveness of post processing techniques.
- Build-to-build and machine-to-machine repeatability. NDE for part dimensioning and defect detection.
- Qualification and Certification. Robust NDE techniques to screen for critical defects.

ASTM E07-F42 NDE of AM Parts Standard



Approach: Incorporate U.S. Air Force Expertise and Findings

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	Optical Method (OM)
Leak Testing	LT	Solid material. Discontinuities.	Through thickness	Detects location	parts where liquid/gas leak tightness reqd.
Liquid Penetrant Testing	PT	Any solid material. Discontinuities - cracks, pores, nicks, others.	Surface breaking	Detects and images location	post-machining reqd., line of sight issues
Process Compensated Resonance Testing	PCRT	Any solid material. Any defect or condition.	Surface and subsurface	Global screening	ASTM E2534
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	correlate R, σ with mechanical props
Alternate Current Potential Drop	ACPD	In electrically conductive material, any condition and/or defect affecting electrical conductivity.	Surface and subsurface	Detects location	correlate σ with microstructure and residual stresses
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	measurement of compressive elastic stresses by peening

Approach: Incorporate U.S. Air Force Expertise and Findings

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

ASTM E07 Committee on Nondestructive Testing

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Committee E07 on Nondestructive Testing

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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

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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.

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ASTM WK47031
Round-Robin Test Distribution

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ASTM WK47031
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ASTM ILS – Quantitative NDT Standard Test Method – Accept/Reject

round-robin testing

Interlaboratory Study Program

Precision and Bias

Additional Information: Ruggedness Testing Pilot Testing

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CONTACT

There are two measurements that serve to express precision in the evaluation of a standard test method. They are commonly referred to as "repeatability" and "reproducibility" and provide the boundaries between which precision exists.

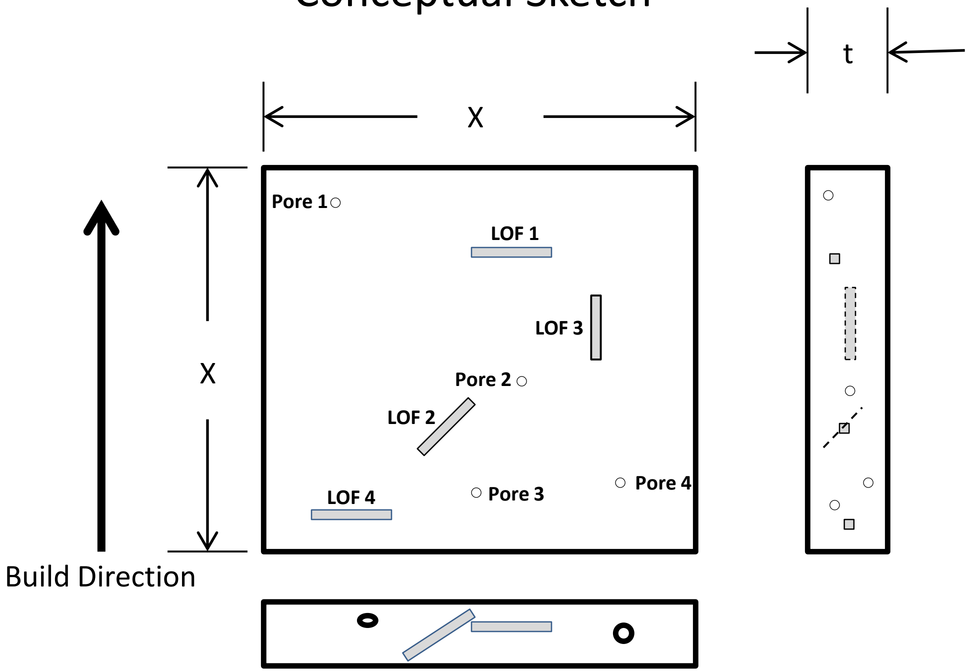
- **Repeatability** - addresses variability between independent test results gathered from within a single laboratory (otherwise known as intralaboratory testing).
- **Reproducibility** - addresses variability among single test results gathered from different laboratories (otherwise known as interlaboratory testing).

Bias, on the other hand, is defined as a systematic error that contributes to the difference between the mean of a large number of test results and an accepted reference value. When included in a standard test method, this statement describes the bias and the methods utilized to provide corrected test results. It is important to remember that if an accepted reference value is not available, then the bias cannot be established. However, if the bias is unknown but the direction or bounds of the bias can be estimated, this information should be included in the bias statement.

As precision and bias are mandatory sections of an ASTM standard test method (per Section A.21 Form and Style for ASTM Standards), the utmost care should be taken to ensure that the final data, as well as the steps that were taken to generate the data, are as precise and accurate as possible. A standard test method that is incapable of doing what it purports can be misleading. Precision and bias statements strengthen the perceived validity of the standard test method and provide the user of the document with the added confidence of knowing that the standard test method has been laboratory tested.

Target – Radiographic & PCRT Sample

Conceptual Sketch



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

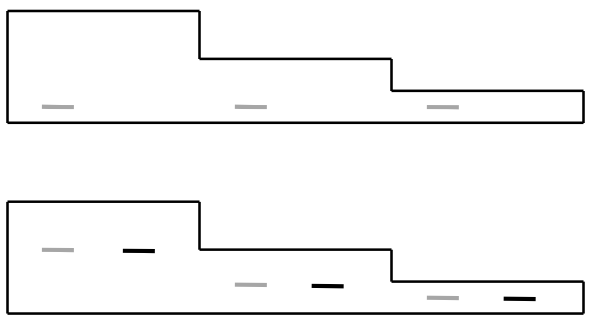
Reference: ASTM E 1320 *"Standard Reference Radiographs for Titanium Castings"*

Target – Ultrasonic Sample (Multiple or 1 thickness) Compare Wrought to AM Primarily used in thickness measurements

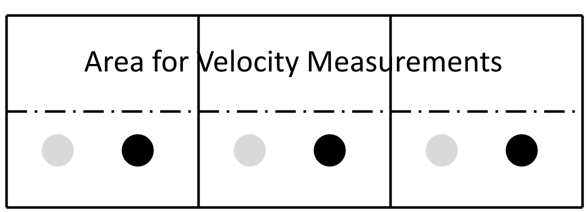
Conceptual Sketches

<u>Stepped vs. One Thickness</u>

Side View

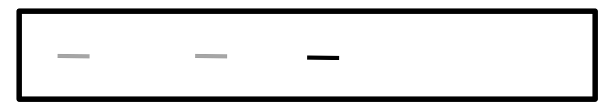


Top View

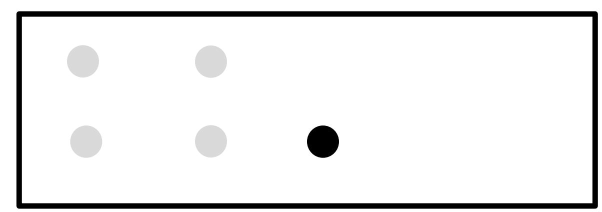


Same plane = Same & Different Mat 'l Thickness

Side View



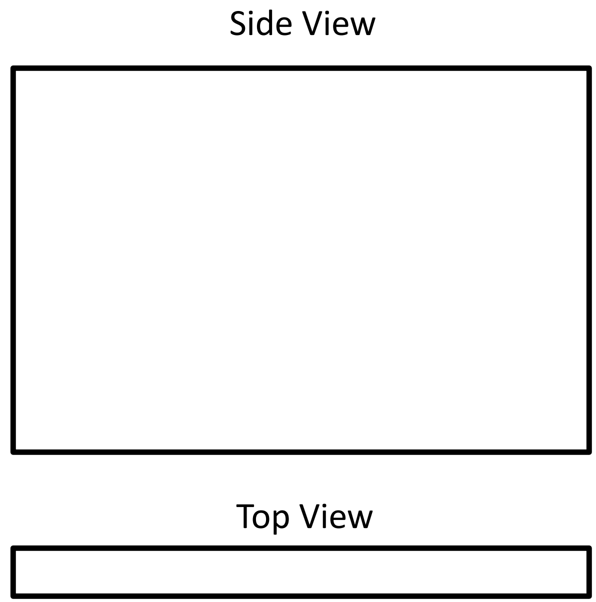
Top View



Lack of Fusion Vary % of t

Flat Bottom Hole

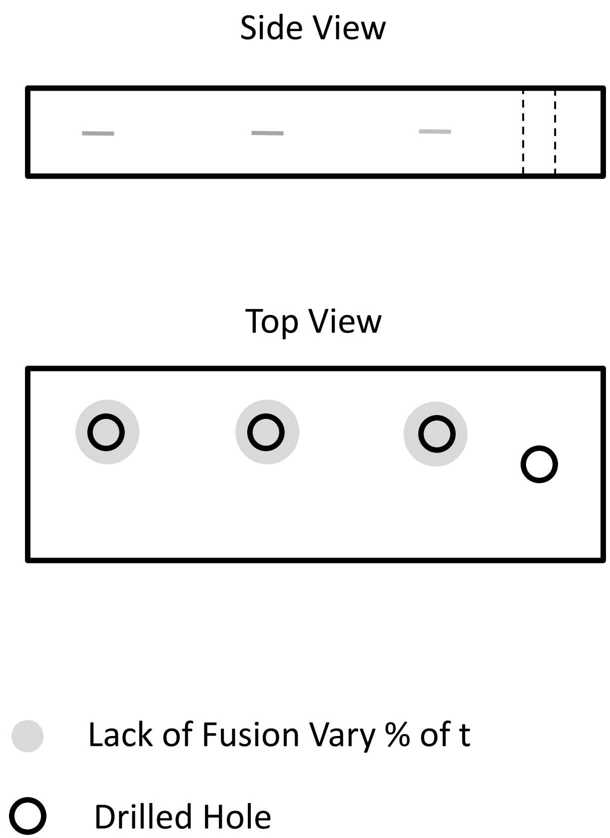
Target – Penetrant Sample (Fatigue Crack or Surface Texture)



Sample uses Fracture Critical Penetrant Crack Panel Experience
An AM panel is fabricated in the orientation to be evaluated. Once built
The panel has an Electrode Discharge Machine (EDM) notch placed on one side
And cycled to grow a through crack for evaluation on the opposite side of
The EDM notch. This allows an evaluation of a tight crack on an as built surface or
The development/technical review of penetrant removal (high background issue)

Target – Eddy Current Sample Compare EDM notches in Wrought to LOF conditions

Conceptual Sketch



Approach: Incorporate European Union NDE of AM Expertise

- **Standardized Qualification Approach of Metallic Additive Manufacturing Processes**
  Florent Lebrun, Beatrice Sandanassamy, THALES ALENIA SPACE
- **Ways to Aerospace Quality with Additive Manufacturing**
  Udo Behrendt, EOS GmbH
- **Qualification of Additive Manufactured Structural Brackets for Space Applications**
  Amy Glover, Andrew Bloyce, Airbus Defence and Space
- **On the Investigation of Processing Parameters and NDT Inspection on Additive Manufacturing Materials for Future Launchers**
  Fernando Lasagni, Amadís Zorrilla, Antonio Periñán, Santos Tudela, CATEC – Center for Advanced Aerospace Technologies; Jorge Vilanova, AIRBUS DEFENCE & SPACE
- **Quality Control in Additive Manufacturing**
  Evelien Winant, Wim Cuypers, GOM Branch Benelux
- **Total Quality Management for Additive Manufacturing**
  Michel Janssens, Materialise
- **Neutron Diffraction NDT of Additive Manufactured Components**
  Mike Curtis-Rouse, Joe Kelleher, STFC

Partial list of presentations given at the Oct. 2014 ESA-sponsored Workshop on Additive Manufacturing for Space Application