

Qualification & Certification of Additively Manufactured Parts for NASA Applications

**NASA Safety Center, Webinar
December 11, 2018**



Welcome and Webinar Objectives

Welcome to Qualification & Certification of Additive Manufactured (AM) Parts for NASA Applications.

This webinar is intended for our NASA Safety and Mission Assurance (S&MA) community to support their significant role in additive manufactured hardware for NASA applications.

Webinar Objectives:

- Reinforce a basic understanding of AM processes.
- Become familiar with MSFC-STD-3716 requirements for metal spaceflight hardware.
- Review key quality assurance products from MSFC-STD-3716.
- Learn about important AM defect types and how to detect them.
- Learn about the challenges and best practices for nondestructive evaluation (NDE) of metal AM parts.

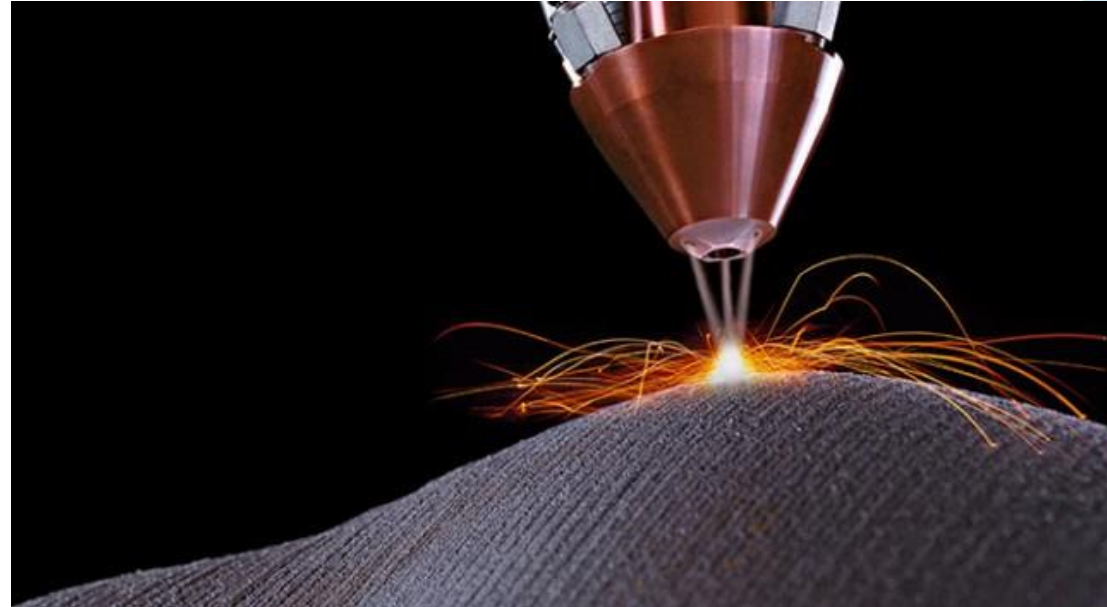
Section 1

Background to Additive Manufacturing

Background



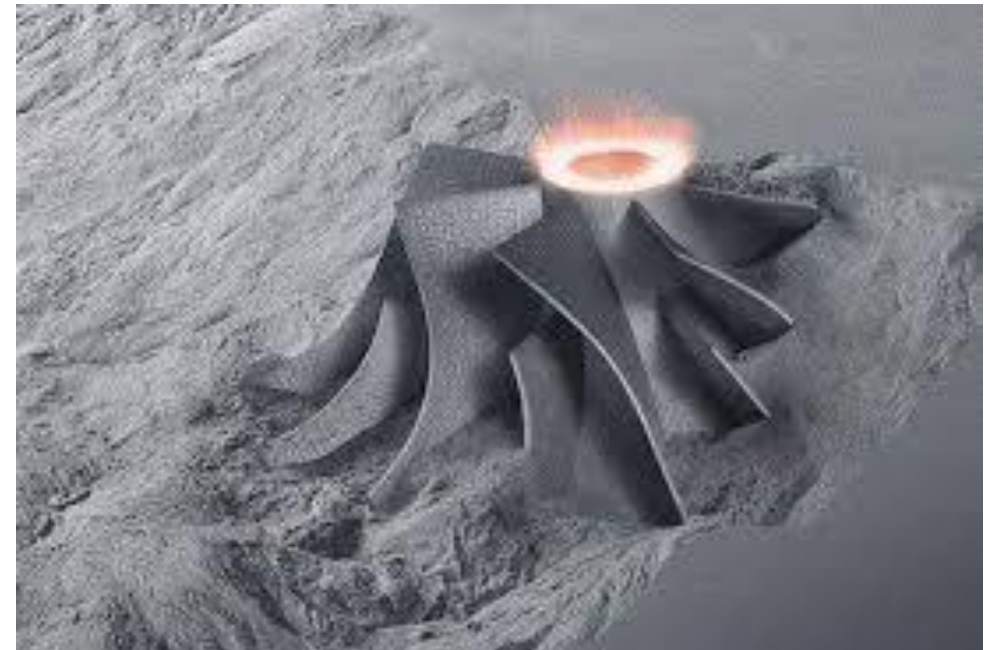
- Additive Manufacturing (AM) is revolutionizing aerospace design and manufacturing.
- AM is the process of building hardware layer by layer with fewer parts yet more complex designs. This reduces costs and waste, while enabling unprecedented design freedom and challenging the order of the traditional aerospace hardware development cycle.
- For existing designs, the cost and time needed to make a part can be reduced, especially for one-of-a-kind or limited quantity production runs common in NASA's programs. Repair of existing hardware is also a possible future application.
- For new designs, reliance on meticulous analysis to mitigate part failure may be reduced since prototype hardware designs can now be iterated (during Design, Development, Test and Evaluation) with reduced cost and impact to schedule.



Background



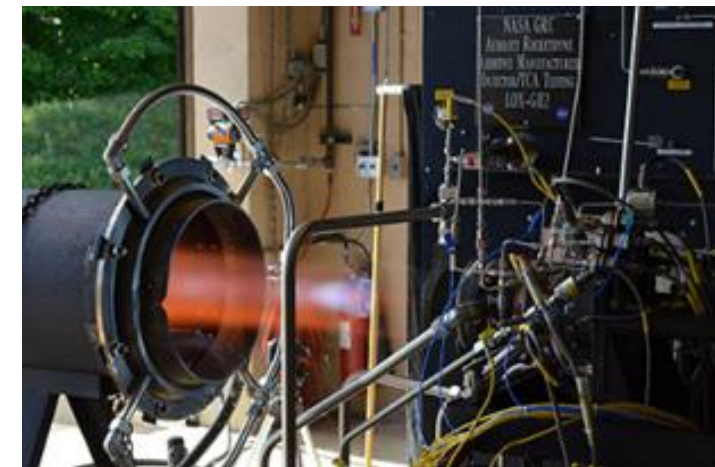
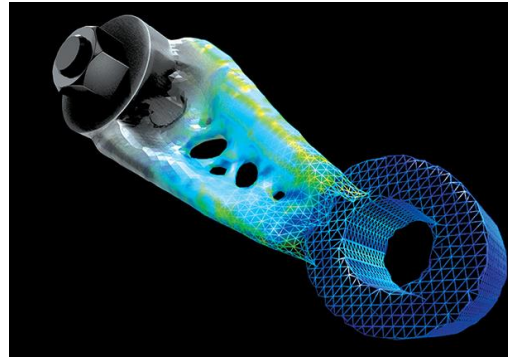
- While other AM processes are mentioned in this webinar, powder bed fusion (PBF) is the current leader among different AM processes for making quality metal aerospace hardware.
- In PBF, metal powder is fused layer-by-layer using a high-energy electron or laser beam. After one layer is fused, a new powder layer is spread on the newly solidified surface, and that layer fused. The process continues until the part rests in a bed of unfused powder, giving PBF its name.
- Multiple factors affect AM part quality:
 - Feedstock consistency
 - Laser power, hatch width, scan rate
 - Thermal conditions during build
 - Build chamber atmosphere
 - Post-processing
 - Worker training
 - Equipment calibration and maintenance
 - And so forth...



Background



- For NASA, Agency standards for the production of consistent, high-quality metallic spaceflight hardware are under development. The only currently available standard is MSFC-STD-3716.
- Requirements in MSFC-STD-3716 establish a methodology to control process variables and manage the risks associated with this new technology.
- A companion specification, MSFC-SPEC-3717, provides detailed procedures for:
 - Equipment calibration and control
 - Personnel training
 - Qualified Metallurgical Process (QMP) development





Definition of Additive Manufacturing (ISO/ASTM 52900-15 Terminology for AM)

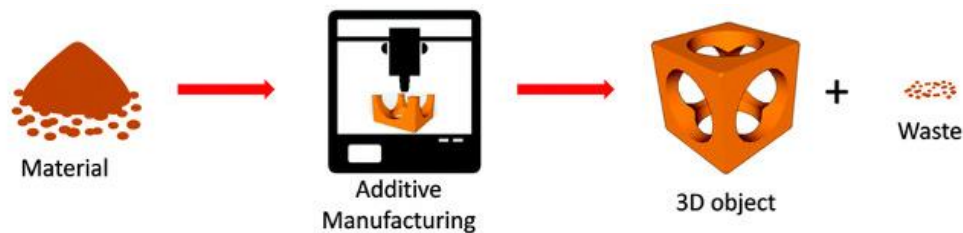
additive manufacturing (AM), n—the process of joining materials to make **parts** from 3D model data, usually **layer** upon layer, as opposed to **subtractive manufacturing** and **formative manufacturing methodologies**.

milling, turning, drilling, EDM etc.

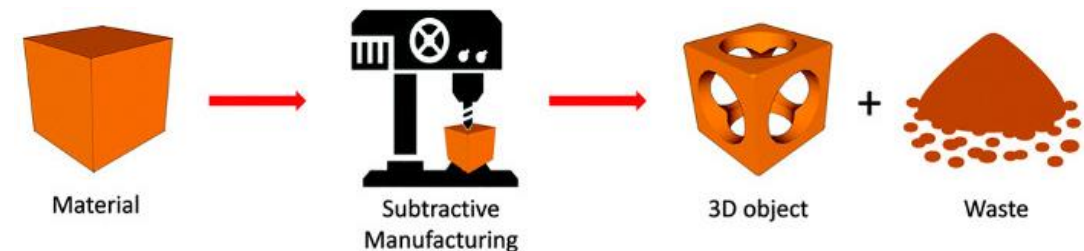
forging, bending, casting, injection molding, compaction of green bodies in powder metallurgy or ceramic processing, etc.

DISCUSSION—The meaning of “additive”, “subtractive” and “formative” manufacturing methodologies are further discussed in [Annex A1](#).

Additive



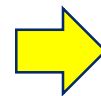
Subtractive



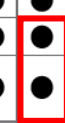
Additive Manufacturing Processes



- **Powder Bed Fusion (PBF)** via:
 - Selective Laser Sintering (**SLS**)
 - Selective Laser Melting (**SLM**)
 - Electron Beam Melting (**EBM**)
- **SLM** and **EBM** parts are *fully* melted during processing.
- **SLS** parts are *partially* melted (sintered) during processing.
- Note: Direct Metal Laser Sintering (**DMLS**), which despite its name, involves full melting of the powder, and thus production of a fully dense part, is not a true sintering process.



AM PROCESS CATEGORY ¹	AM PROCESS TYPE	MATERIAL			BINDER OR FUSION MECHANISM						FEEDSTOCK FORM			
		METALS	POLYMERS	CERAMICS	LASER BEAM	ELECTRON BEAM	PLASMA ARC	ULTRAVIOLET	LIQUID BINDING AGENT	ULTRASONIC	OTHER HEAT / POST-PROCESSING	POWDER	FILAMENT	RESIN	SHEET
Binder Jetting	---	●	●	●					●		●		●	
Directed Energy Deposition	Blown Powder	●	●	●	●						●	●		
	Ion Fusion Formation	●					●				●		●	
	Electron Beam Direct Manufacturing	●				●					●		●	
Material Extrusion	Fused Deposition Modeling		●								●		●	
	Multiphase Jet Solidification	●	●	●							●	●	●	
Material Jetting	---		●					●						●
Powder Bed Fusion	Laser Sintering		●	●	●						●	●		●
	Laser Melting	●			●						●	●		
	Electron Beam Melting	●				●					●	●		
Sheet Lamination	Laminated Object Manufacturing	●	●	●							●	●		●
	Ultrasonic Consolidation	●							●		●			●
Vat Photo-polymerization	---		●	●					●		●		●	



Additive Manufacturing Processes



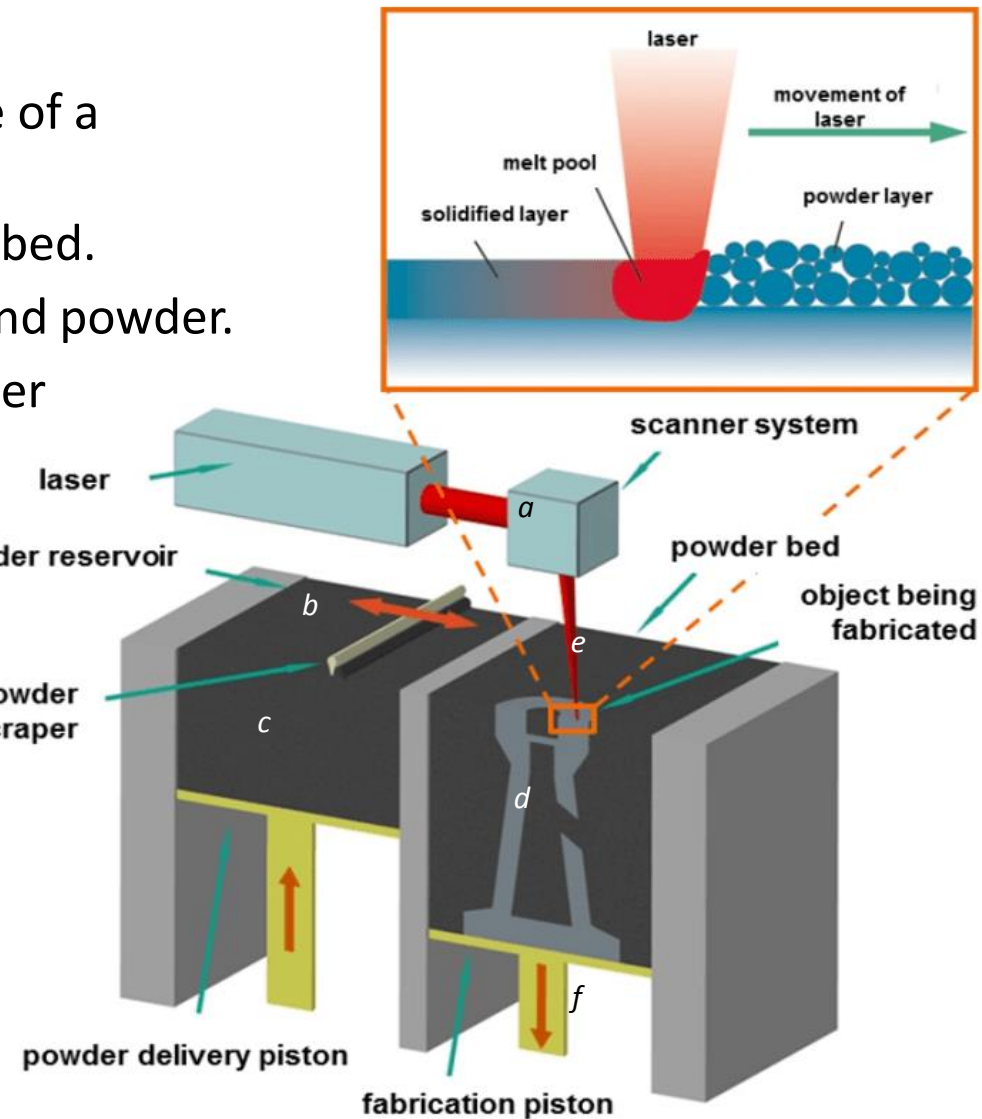
- **Powder Bed Fusion (PBF)**

- A moving head *a*) selectively binds the surface of a powder bed *e*).
- A moving platform *f*) progressively lowers the bed.
- The solidified object *d*) rests inside the unbound powder.
- New powder is added to the bed from a powder reservoir *c*) by means of a powder scraper (recoater blade) *b*).

- A thin layer (≤ 0.001 in.) of metal powder is melted (or sintered) by finely focused laser rastering across the build area.

- The scale of SLM is limited:

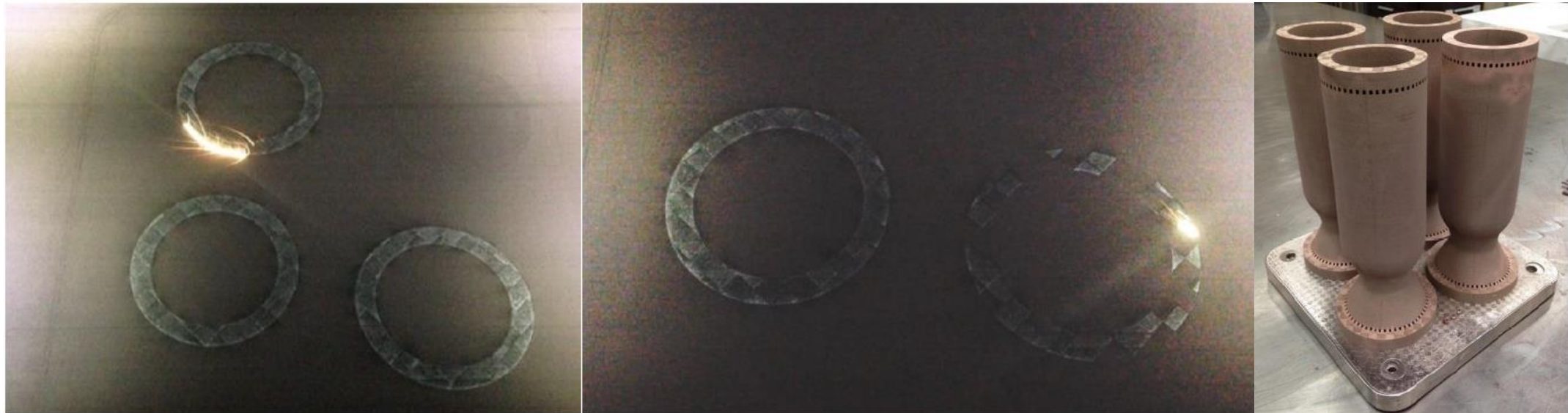
- Common: 250×250×325 mm
- Large: 800×400×500 mm
- New target: >1000 mm dimension



Additive Manufacturing Processes



- **Powder Bed Fusion (PBF)**
- Combustion chamber liner fabrication showing the contouring (outside edges) pass (left), in-fill pass (middle), and finish liners (right)



Additive Manufacturing Processes



- **Directed Energy Deposition (DED)** via:
 - Electron Beam Additive Manufacturing (**EBAM**)
 - Electron Beam Free Form Fabrication (**EBF³**)



- Uses numerous welding wire products (Ti, Al, Ni, and Co alloys, 300 Series SS, niobium, tungsten, tantalum, and molybdenum)
- Faster than PBF
- Part size limited by vacuum chamber size
- Near 100% wire feed usage efficiency
- Functionally graded materials (FGMs) possible
- Blown powder can be used if a laser energy source is used.



AM PROCESS CATEGORY ¹	AM PROCESS TYPE	MATERIAL			BINDER OR FUSION MECHANISM						FEEDSTOCK FORM				
		METALS	POLYMERS	CERAMICS	LASER BEAM	ELECTRON BEAM	PLASMA ARC	ULTRAVIOLET	LIQUID BINDING AGENT	ULTRASONIC	OTHER HEAT / POST-PROCESSING	POWDER	FILAMENT	RESIN	SHEET
Binder Jetting	---	●	●	●					●		●			●	
Directed Energy Deposition	Blown Powder	●	●	●	●						●	●			
	Ion Fusion Formation	●					●				●		●		
	Electron Beam Direct Manufacturing	●				●					●		●		
Material Extrusion	Fused Deposition Modeling		●								●		●		
	Multiphase Jet Solidification	●	●	●							●	●	●		
Material Jetting	---		●					●						●	
Powder Bed Fusion	Laser Sintering		●	●	●						●	●		●	
	Laser Melting	●			●						●	●			
	Electron Beam Melting	●				●					●	●			
Sheet Lamination	Laminated Object Manufacturing	●	●	●							●	●			●
	Ultrasonic Consolidation	●							●		●				●
Vat Photo-polymerization	---		●	●					●		●		●		

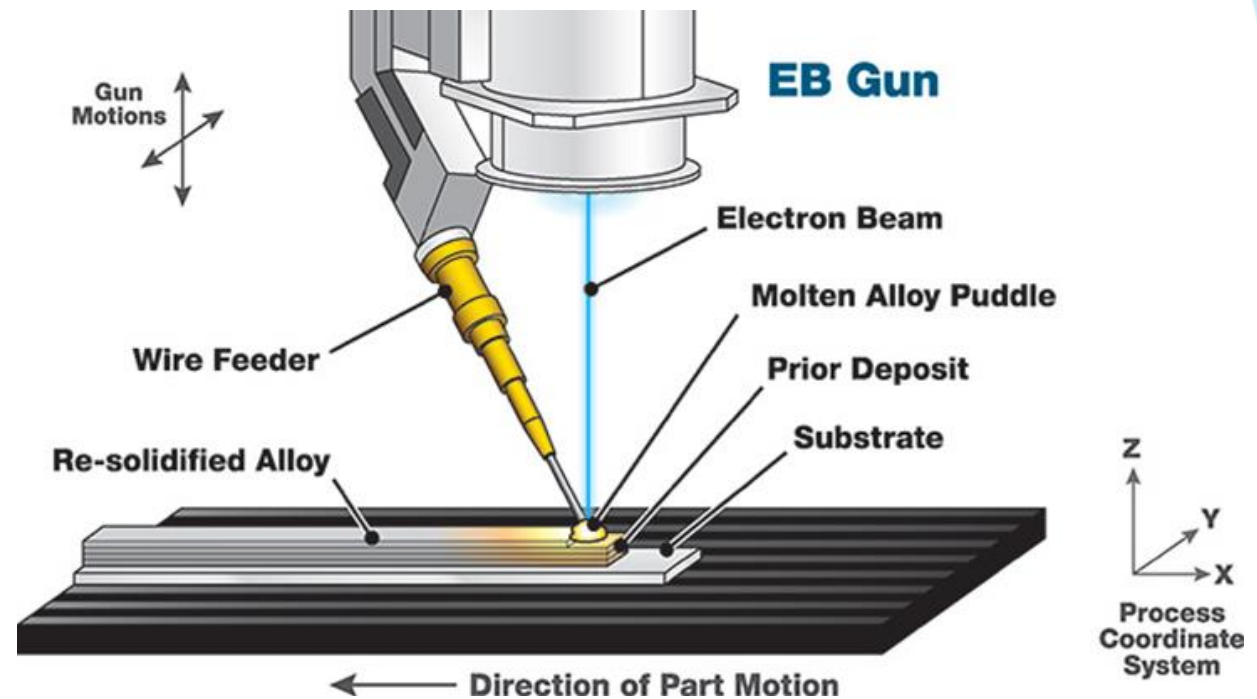


Additive Manufacturing Processes



- **Directed Energy Deposition (DED)**

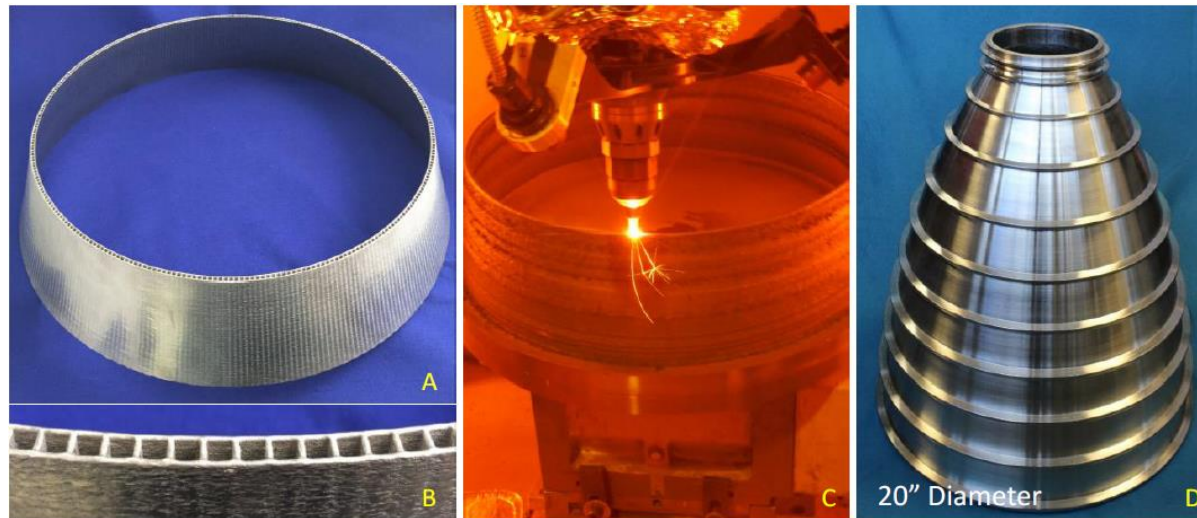
- Uses wire feedstock and an electron beam (EB) or plasma arc heat source to deposit metal.
- Produces a near-net shape part inside a vacuum chamber.
- Once the part reaches near-net shape, it undergoes finish heat treatment and machining.





Additive Manufacturing Processes

- **Directed Energy Deposition (DED)**
 - Make components larger than those made using PBF.
 - Used to close out coolant channels for nozzles and chambers, for example, Laser Wire Direct Closeout (LWDC) structures.
 - Also have laser wire (previous slide), blown powder (below), arc-weld, and electron beam wire deposition methods.

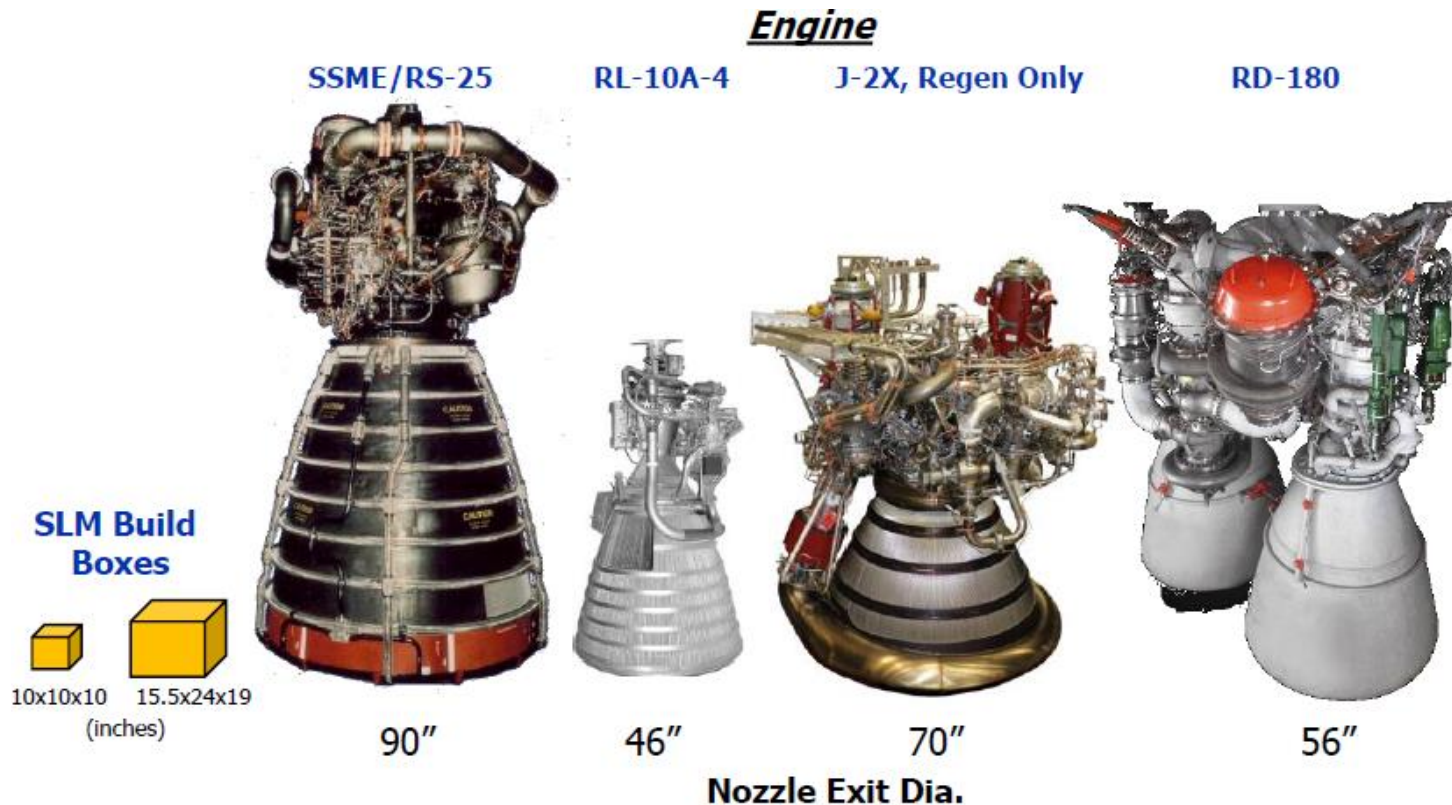


DED blown powder deposition: A. Channel wall nozzle with integral channels, B. as-built integral channels, C. in-process DED fabrication of subscale nozzle jacket, D. Final-machined nozzle jacket.

Metal Additive Manufacturing Processes



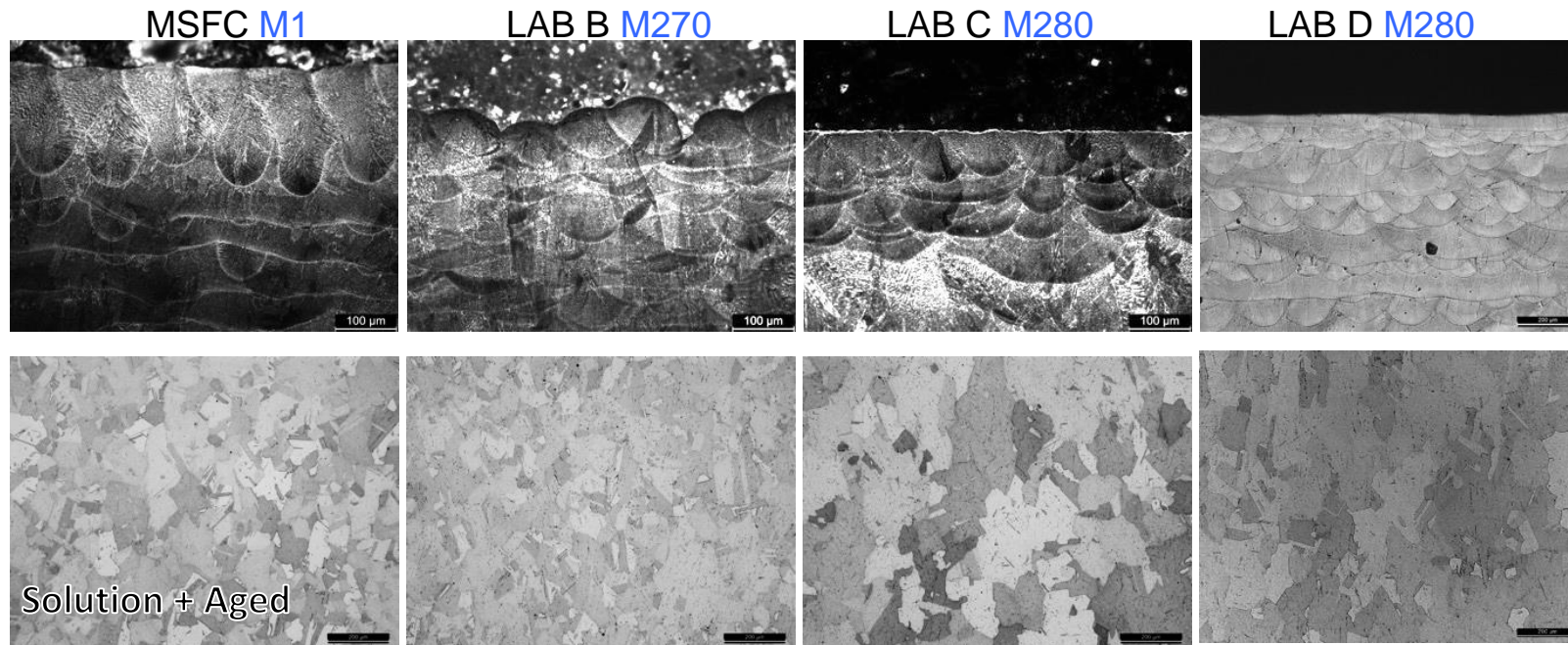
- NASA has been investigating various AM methods for liquid rocket engine channel wall nozzles to further reduce cost and schedule. The methods being evaluated are targeting increased scale required for current NASA and commercial space programs, well beyond SLM capabilities.





Post-Processing

- As-built microstructures are dominated by the characteristics of the melt pool (top micrographs).
- Following heat treatment and/or Hot Isostatic Pressing (HIP), the microstructure recrystallizes and resembles the wrought microstructure, with some expected grain size variation (bottom micrographs).

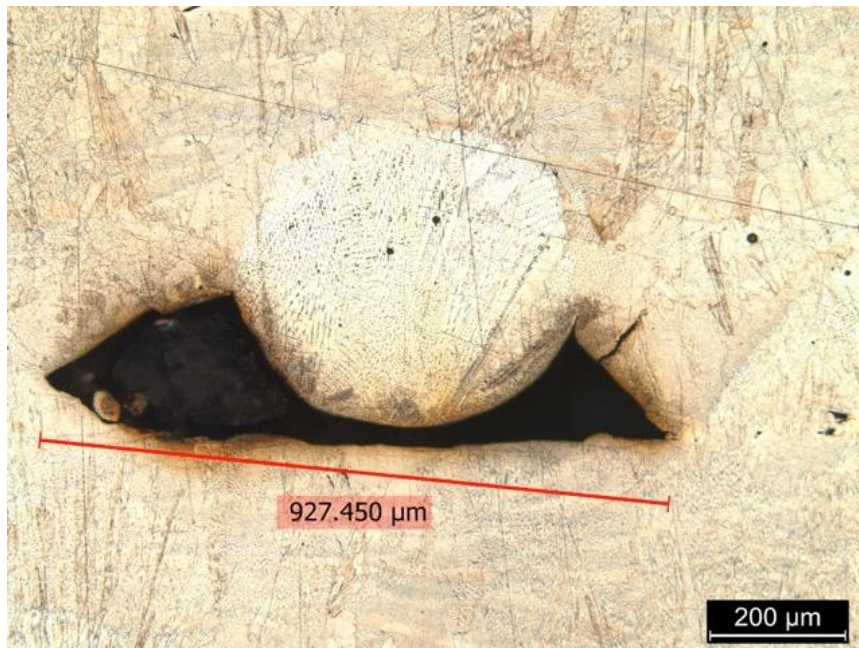


Source: Brown, A., Jones, Z. Tilson, W., *Classification, Effects, and Prevention of Build Defects in Powder-bed Fusion Printed Inconel 718*, NASA Marshall Space Flight Center, 2016.



Post-Processing

- As-built parts also show the presence of voids (left micrograph) caused by low power, high scan rate, attenuated laser (from fogging of the laser lens, for example), or in the case shown below, spatter (molten ejecta) falling on surface during build. After heat treatment and/or HIP, such lack of fusion (LOF) defects are closed (right micrograph):



Lack of fusion defect caused by spatter

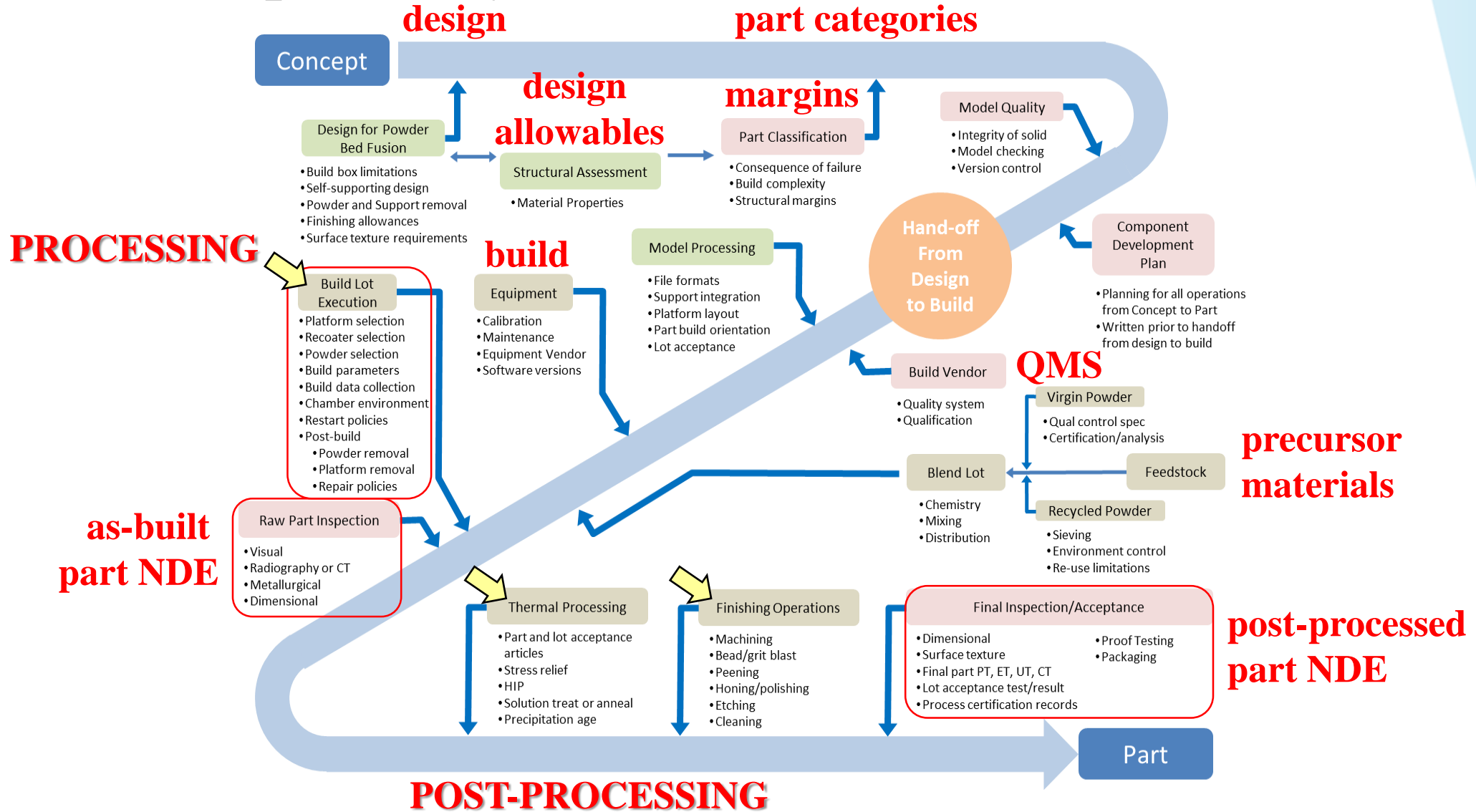


Lack of fusion defect after HIP

Source: Brown, A., Jones, Z. Tilson, W., *Classification, Effects, and Prevention of Build Defects in Powder-bed Fusion Printed Inconel 718*, NASA Marshall Space Flight Center, 2016.

Processing and Post-Processing

Relative to AM part life cycle



Section 2

**Additive Manufacturing,
Examples of Aerospace Applications**



Metal Aerospace AM Parts

Example 1



NASA MSFC rocket **injectors** made by traditional means took more than a year to make, but with AM took less than four months, resulting in a 70% reduction in cost.

- Using traditional manufacturing methods, 163 parts are made, which must then be assembled by welding
- With AM, only 2 parts are needed, saving time and money, and allowing engineers to enhance rocket engine performance while being less prone to failure.
- Liquid Rocket Engines with 100 to 35,000 lb_f thrust have been manufactured with AM hardware, including injectors, injector faceplates, regeneratively-cooled combustion chambers and nozzles, gas generators, preburners, and augmented spark igniters.



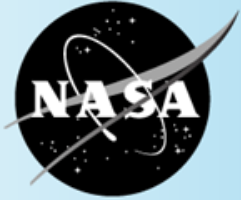
28-element Inconel[®] 625 fuel injector built using an laser powder bed fusion (L-PBF) process



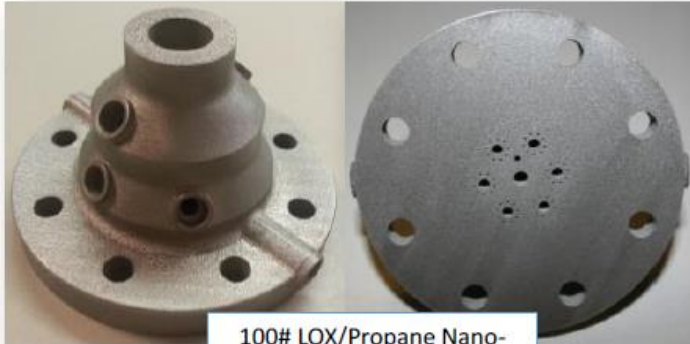
Hot fire test using L-PBF injectors

Metal Aerospace AM Parts

Example 1 (cont.)



SLM Injectors fabricated and tested at MSFC.



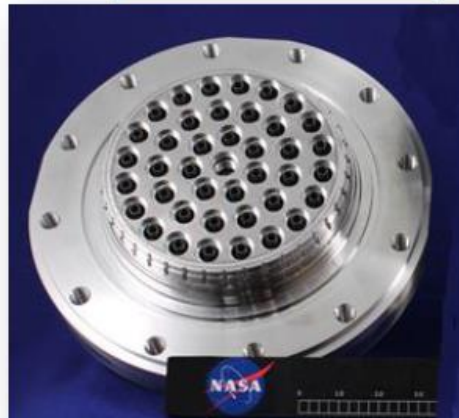
100# LOX/Propane Nano-launch Injector Built 2012
Tested Nov 2013



1.2K LOX/Hydrogen Injector
First Tested June 2013
>7200 sec hotfire



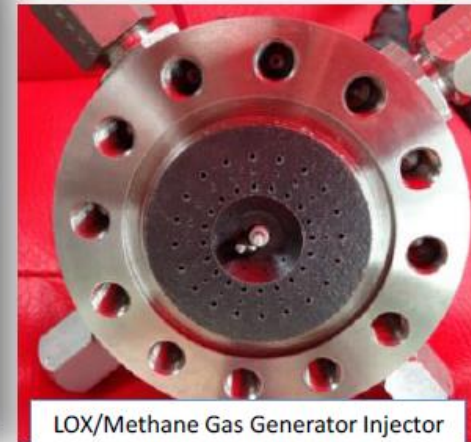
20K LPS Subscale Injector Tested Aug 2013
(3) Subscale Injectors Tested



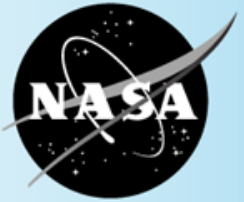
Methane 4K Injector
Printed manifolds and parametric feature
Tested Sept 2015



35K AMDE Injector with Welded Manifolds
First Tested Nov 2015



LOX/Methane Gas Generator Injector
Tested Summer 2017



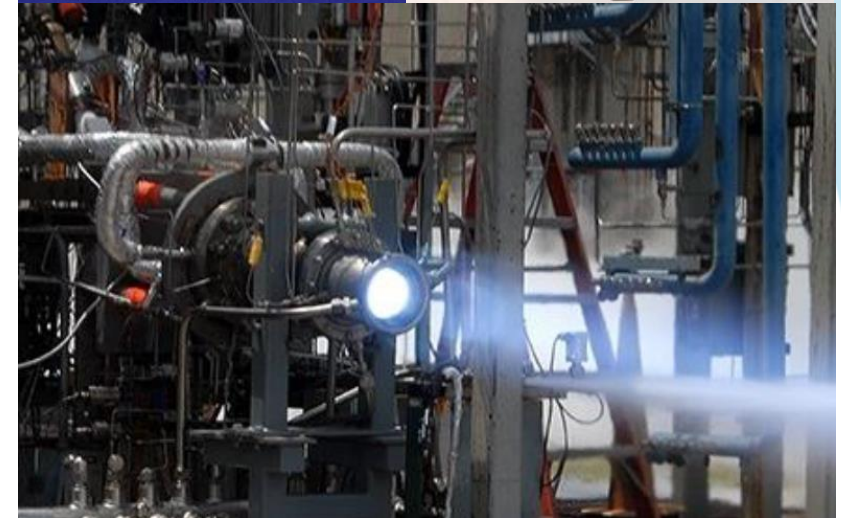
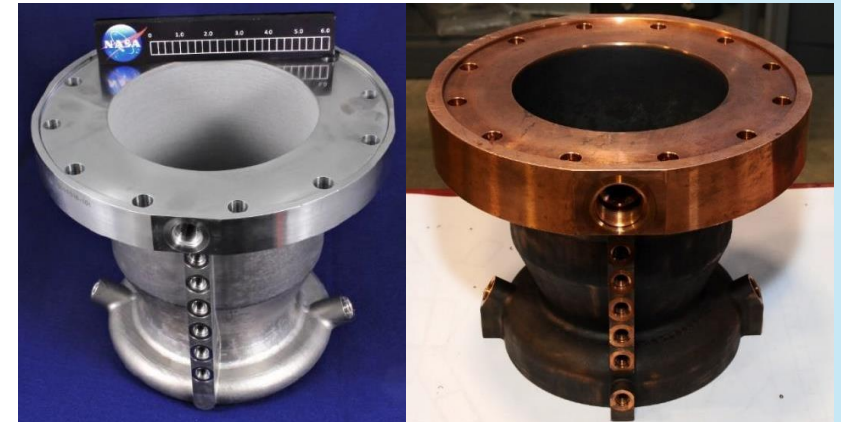
Metal Aerospace AM Parts

Example 2



NASA MSFC has also built channel-cooled **combustion chambers** using L-PBF, but that use bi-metallic additive and hybrid techniques.

- The materials used vary from Inconel® 625 and 718, Monel® K-500, GRCo-84, and C18150 metal alloys.
- The thrust chamber designs tested ranged from 200 to 1,400 psia in a variety of propellants and mixture ratios, producing 1,000 to 35,000 lb_f thrust.
- Workhorse chamber liners, bi-metallic chambers, augmented spark igniters, and larger scale channel-cooled nozzles have also been made.



LOX/methane Inconel® and GRCo-84 chamber throat sections and hot-fire testing

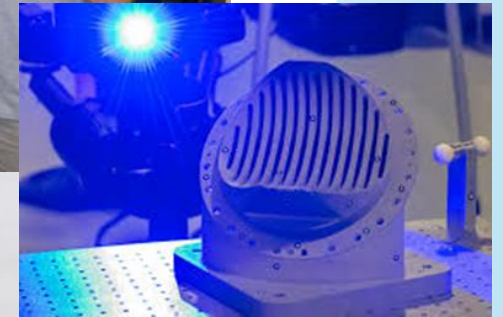


Metal Aerospace AM Parts

Example 3



- **AEROJET ROCKETDYNE** Engineers successfully hot-fire tested a heritage RS-25 rocket engine retrofitted with a pogo accumulator, which regulates LOX movement during flight to prevent destabilizing vibrations:
 - Simpler: over 100 welds eliminated
 - More affordable: costs reduced by nearly 35% and production time by more than 80%
- Welds require inspection and possible rework, and are points of possible failure; therefore, eliminating them reduces production costs and increases part reliability.



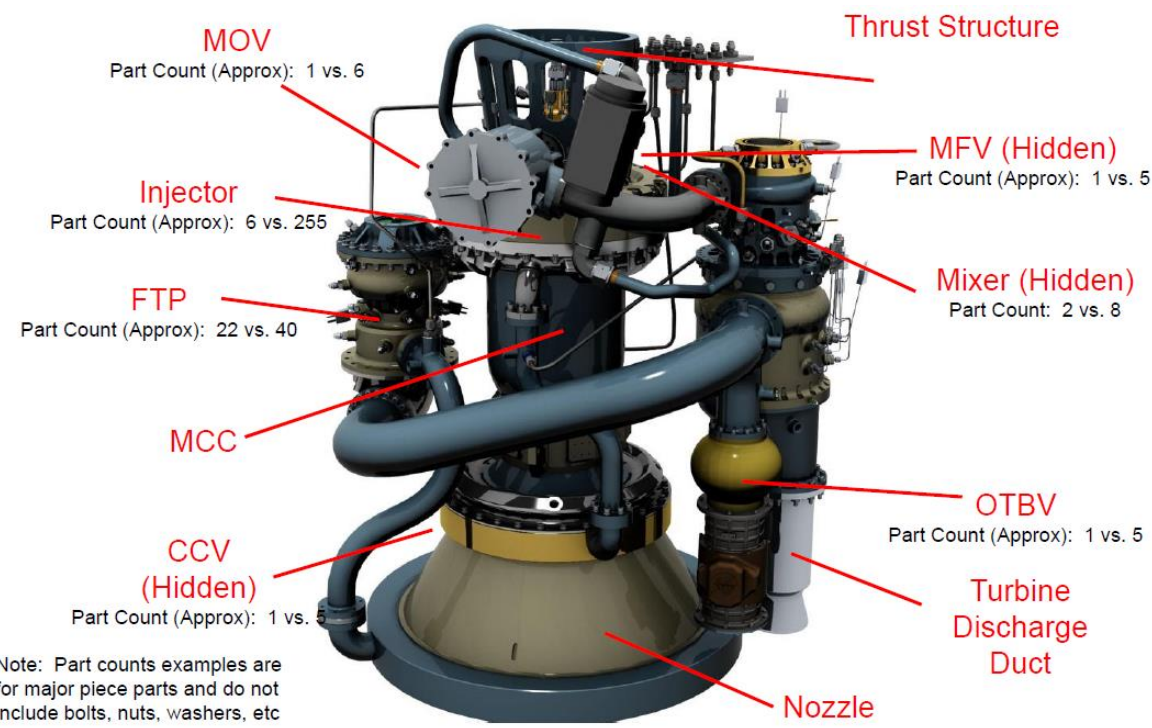
A technician for NASA's RS-25 prime contractor exhibits the pogo accumulator (top and middle), which was subsequently hot-fire tested (bottom)

Metal Aerospace AM Parts

In Summary



- In addition to reductions in Design, Development, Test and Evaluation (DDT&E) time (7-10 years to 2-4 years), hardware lead time (3-6 years to 6 months), and costs (order-of-magnitude reductions possible), part counts can be dramatically reduced:



Reduction in parts count for a rocket engine

Section 3

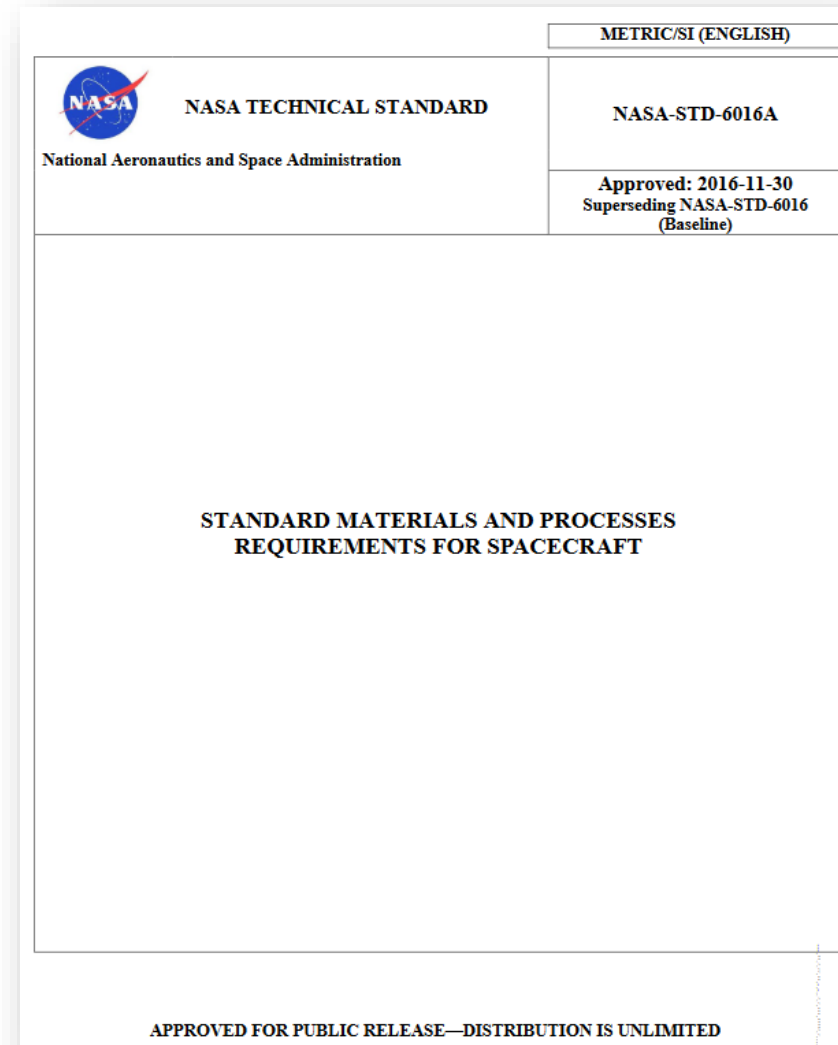
Governing Standards



Definition of Additive Manufacturing


(NASA-STD-6016A Standard Materials and Processes Requirements For Spacecraft)

Additive Manufacturing: Any process for making a three-dimensional object from a 3-D model or other electronic data source primarily through processes in which successive layers of material are deposited under computer control.



NASA-STD-6016A

Standard Materials and Processes Requirements For Spacecraft[§]

		METRIC/SI (ENGLISH)
	NASA TECHNICAL STANDARD	NASA-STD-6016A
National Aeronautics and Space Administration		Approved: 2016-11-30 Superseding NASA-STD-6016 (Baseline)



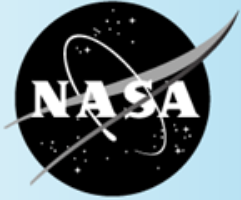
- *Guidelines documents and standards for additive manufacturing are in development at this time. The requirements of this NASA Technical Standard on M&P controls, materials design values, metallic and nonmetallic materials, and nondestructive inspection apply to hardware manufactured by additive techniques, just as they do for traditional manufacturing techniques.*
- *For nonstructural, nonmetallic 3-D printed hardware, controlled and verified processes are essential; but other M&P aspects like flammability, toxic offgassing, and vacuum outgassing also apply, just as for any other nonmetallic material.*
- *When structural hardware is manufactured by additive manufacturing techniques, a manufacturing and qualification plan shall be submitted to NASA and approved by the responsible NASA M&P and design organizations.*

[§] guidance (italics) and requirements excerpts from NASA-STD-6016A

NASA-STD-6016A

Standard Materials and Processes Requirements For Spacecraft[§]

 NASA TECHNICAL STANDARD National Aeronautics and Space Administration		METRIC/SI (ENGLISH)
		NASA-STD-6016A
		Approved: 2016-11-30 Superseding NASA-STD-6016 (Baseline)



- *Key aspects of producing structural metallic hardware by additive manufacturing techniques, such as direct metal laser sintering (DMLS) and selective laser melting (SLM), include proper development of structural design values and controlled processes, although other requirements, such as stress-corrosion resistance and corrosion control, also apply. Verification of appropriate process control should include first article inspection to verify proper material properties and macro/microstructure and mechanical property testing of integrally manufactured specimens from each hardware unit.*

[§] guidance (italics) excerpts from NASA-STD-6016A

Active Standards for AM within NASA: MSFC-STD-3716 & MSFC-SPEC-3717



<https://www.nasa.gov/sites/default/files/atoms/files/msfcstd3716baseline.pdf>
<https://www.nasa.gov/sites/default/files/atoms/files/msfcspec3717baseline.pdf>

Released Oct. 18, 2017

Developing NASA Agency-Level Standards



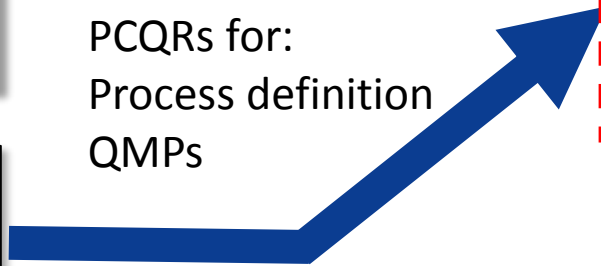
MSFC-STD-3716



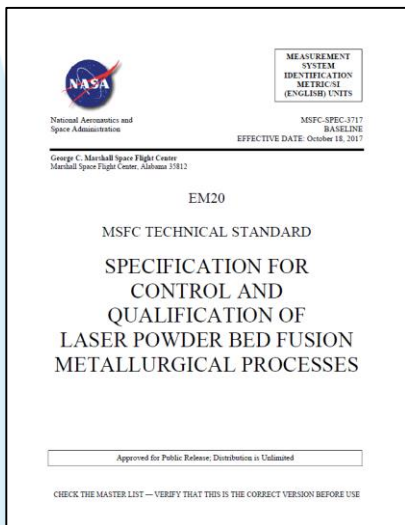
65 AMRs



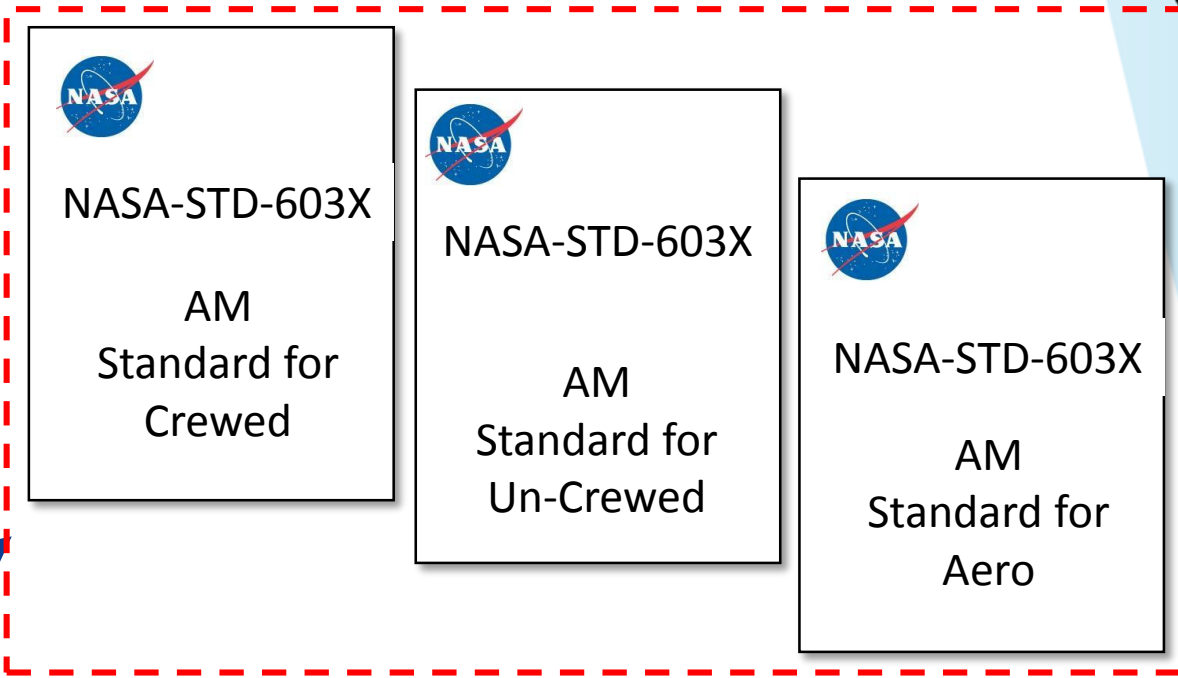
PCQRs for:
Process definition
QMPs




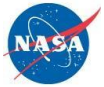
MSFC-SPEC-3717




PCQRs for:
Equipment and facility process control




NASA-STD-603X
AM
Standard for
Crewed


NASA-STD-603X
AM
Standard for
Un-Crewed

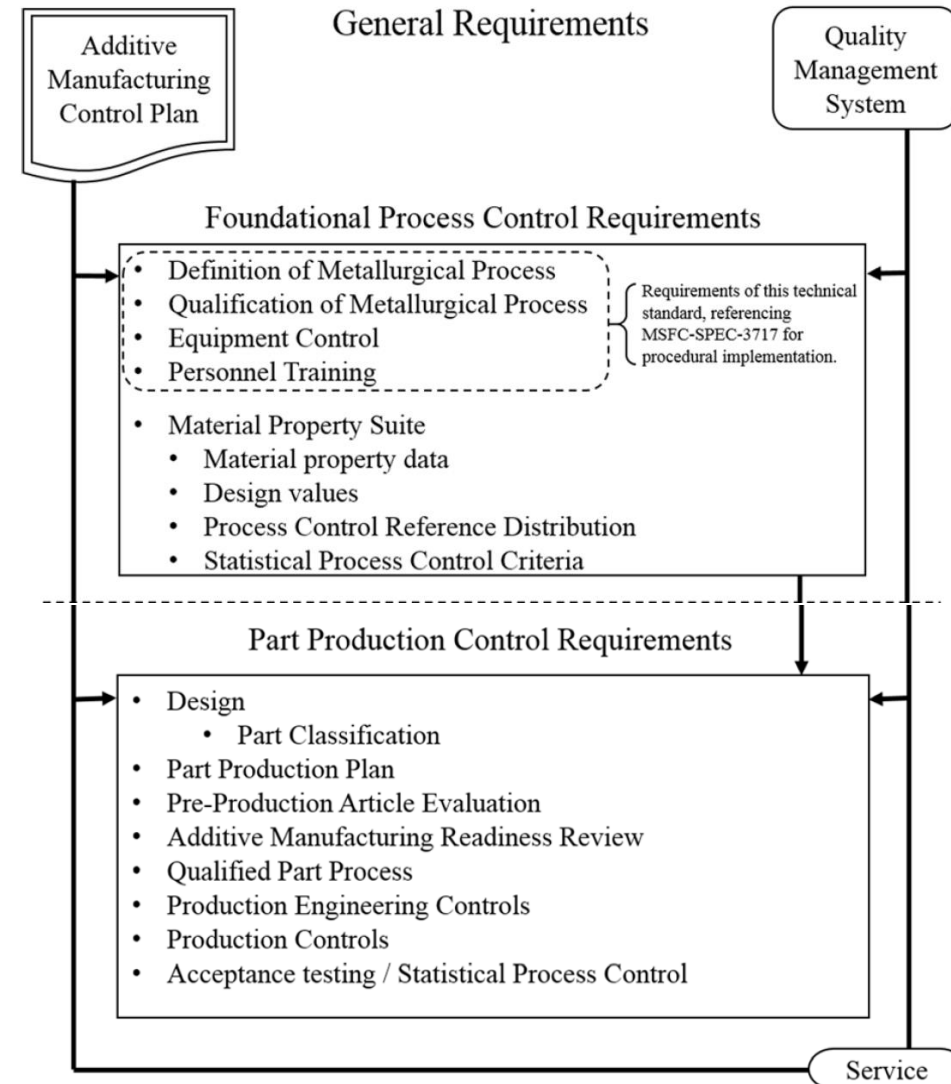

NASA-STD-603X
AM
Standard for
Aero


NASA-SPEC-603X
AM Spec for
Equip and
Fac.

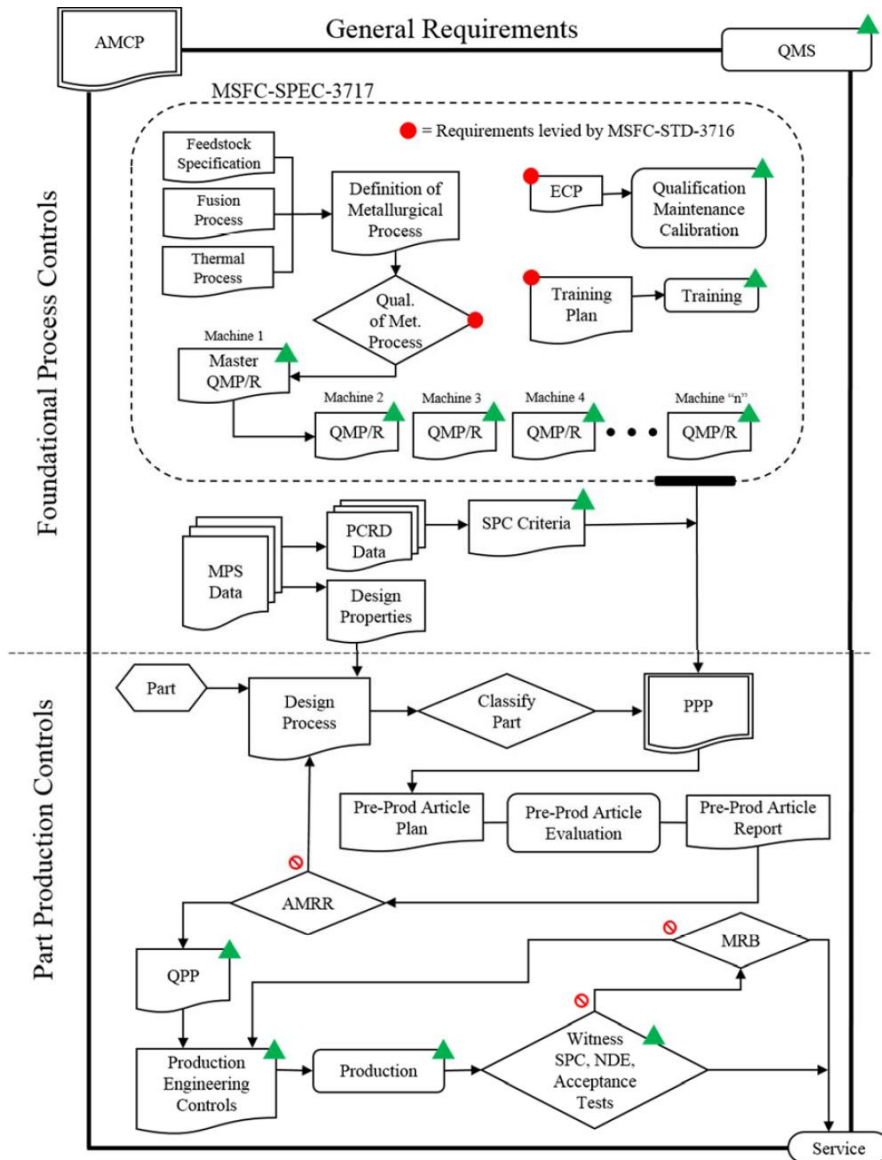


MSFC-STD-3716 Outline

- General requirements govern the engineering and production practice and are paralleled by a Quality Management System (QMS).
- Process control requirements provide the basis for reliable part design and production and include:
 - qualified metallurgical processes (QMPs)
 - equipment controls (ECP)
 - personnel training
 - material property development
- Part Production Control requirements are typical of aerospace operations and must be met before placing a part into service.



MSFC-STD-3716/MSFC-SPEC-3717 Outline



Foundational Process Controls provide the basis for reliable part design and production

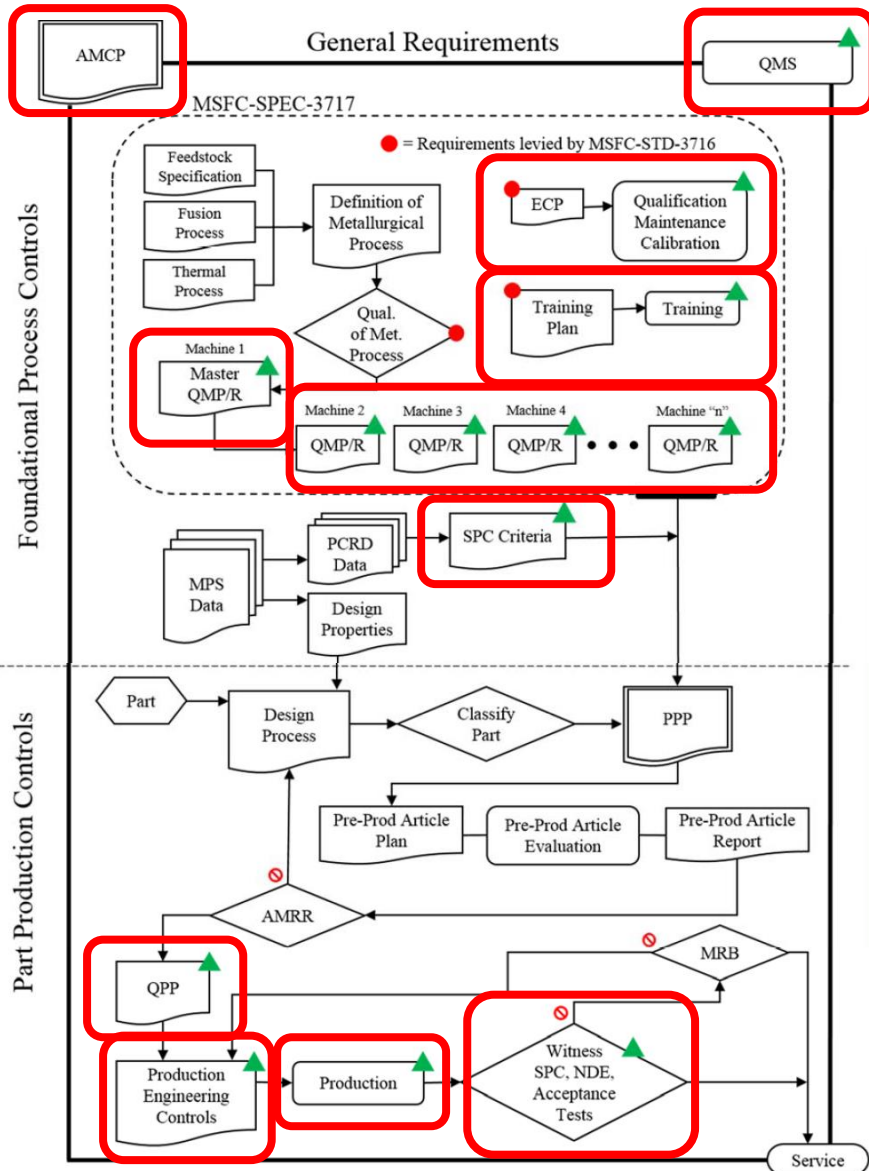


- ▲ Identifies key points of QMS involvement.
- Identifies PBF requirements levied by MSFC-STD-3716 with procedures in MSFC-SPEC-3717
- ⊘ Negative outcome of decisional action

Part Production Controls are typical of aerospace operations and include design, part classification, pre-production and production controls



Key Quality Assurance Products



Key Quality Assurance Products

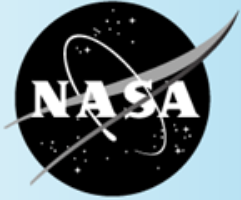
- Quality Management System, AS9100 (QMS)
- Additive Manufacturing Control Plan (AMCP)
- Equipment and Facility Control Plan (EFCP)
- Training Plan/Program
- Qualified Metallurgical Process Records (QMP)
- Statistical Process Controls
- Qualified Part Process (QPP)
- Production Engineering Controls
- Production Process Controls
- Acceptance Testing
 - Witness Testing
 - NDE

Key Quality Assurance Products



- **Quality Management System, AS9100 (QMS)**
 - [AMR-4] The CEO shall ensure a QMS conforming to SAE AS9100, Quality Management Systems – Requirements for Aviation, Space and Defense Organizations, or an approved equivalent, is in place and active at all entities involved in the design and production of L-PBF hardware
- **Additive Manufacturing Control Plan (AMCP)**
 - [AMR-3] The CEO responsible for the design and manufacture of L-PBF hardware shall provide an AMCP that accomplishes each of the following:
 - a) Documents the implementation of each of the requirements of this MSFC Technical Standard.
 - b) Documents and provides rationale for any tailoring of the requirements of this MSFC Technical Standard.
 - c) Documents the methods used to control compliance with these requirements by subcontractors and vendors.
 - d) Provides for complete governance for the implementation of L-PBF such that, once approved by the procuring authority, the AMCP becomes the document used for verification of L-PBF requirements.

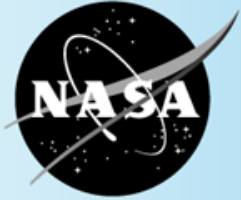
Key Quality Assurance Products



- **Equipment and Facility Control Plan (EFCP)**

- [PCQR-24] An Equipment and Facility Control Plan (EFCP) shall be developed and maintained within the QMS that addresses, at minimum, the implementation of the requirements of L-PBF equipment and facility control of Section 4.5 and its subsections.
- Examples of EFCP Controls
 - Feedstock Storage and Handling
 - Contamination and FOD control
 - Computer and Data Security
 - Operational Procedures and Checklists
 - Configurational Management of AM machines and equipment
 - Maintenance and Calibration
 - Machine Qualification

Key Quality Assurance Products



- **Training Plan/Program**

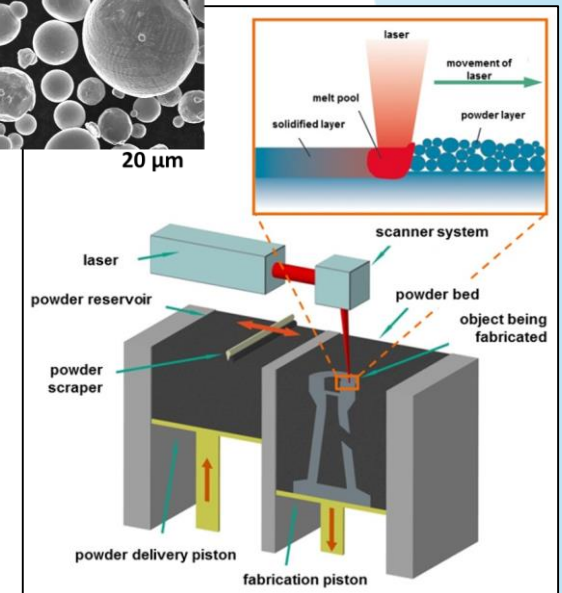
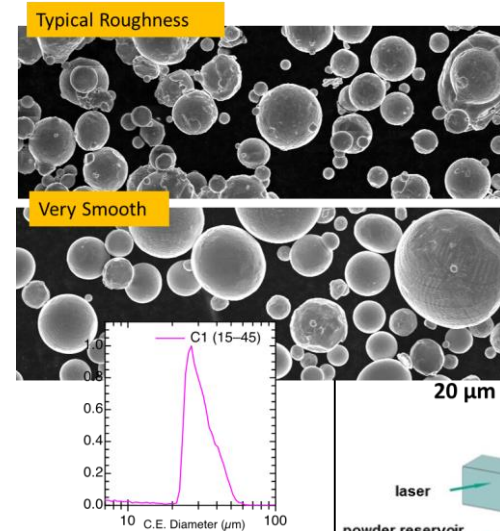
- [PCQR-45] An active operator training program shall be defined, maintained, and implemented to meet the following objectives:
 - a) Provide a consistent framework for training and certification requirements
 - b) Provide clear delineations of abilities and responsibilities associated with granted certifications
 - c) Provide operators with all necessary skills, knowledge, and experience to execute the responsibilities of their certification safely and reliably
 - d) Provide for operator evaluations that demonstrate adequacy in skills, knowledge, and experience to grant certifications to personnel, ensuring only properly trained and experienced personnel have appropriate certifications
 - e) Incorporate content regarding the importance, purpose, and use of the QMS for all certifications.

Key Quality Assurance Products



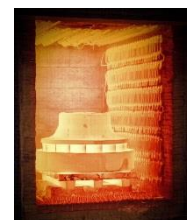
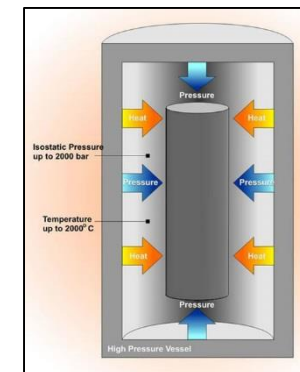
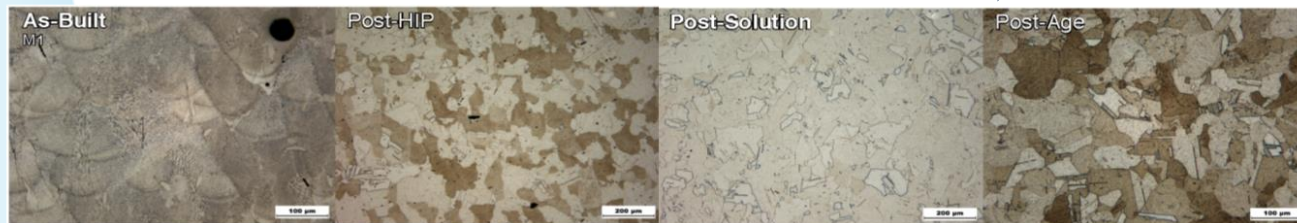
- **Qualified Metallurgical Process (QMP) Records**

- Begins as a **Candidate** Metallurgical Process
- Defines aspects of the basic, **part agnostic**, fixed AM process including:
 1. Feedstock
 2. Fusion Process
 3. Thermal Post-Process
- **Qualification** of candidate process through rigorous evaluations
- Enabling concept
 - Machine qualification and re-qualification
 - Process control metrics, SPC
 - Design values



Source: Fraunhofer IWU

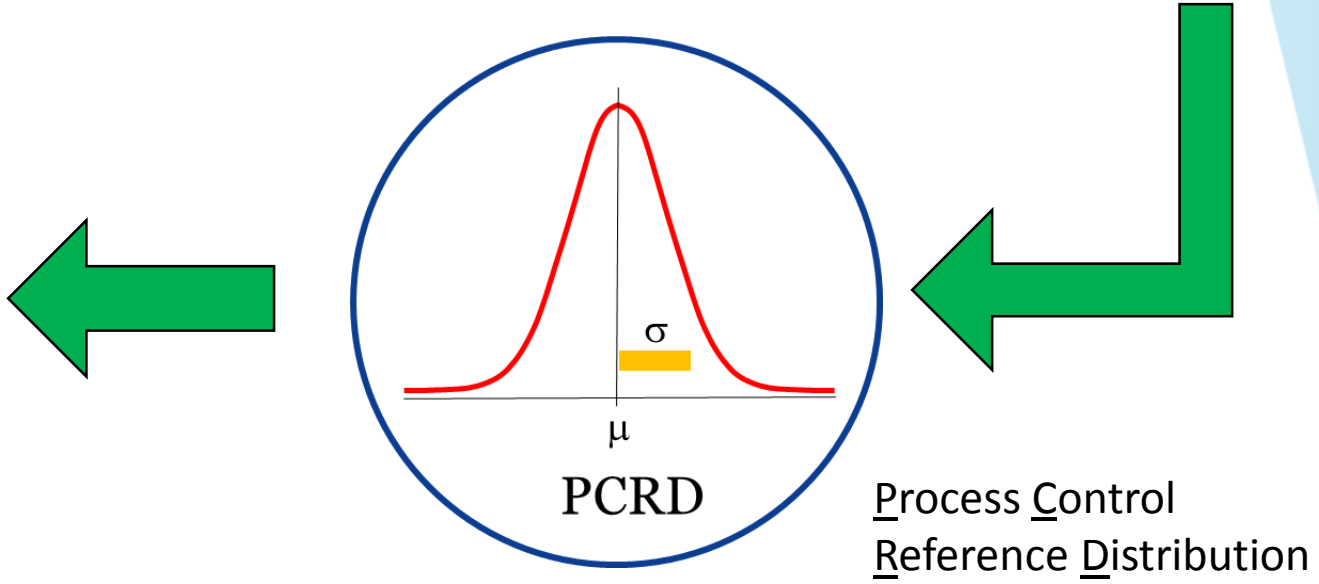
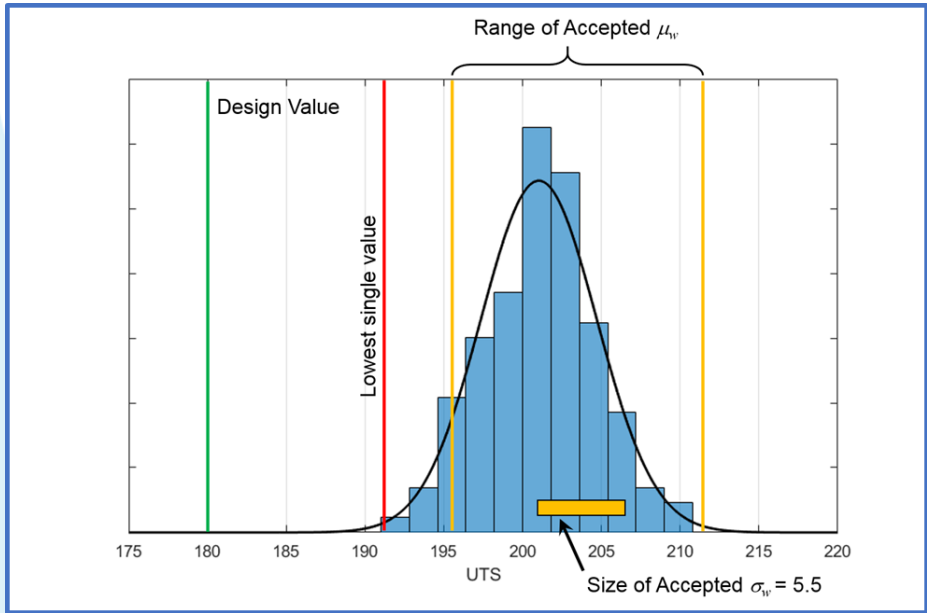
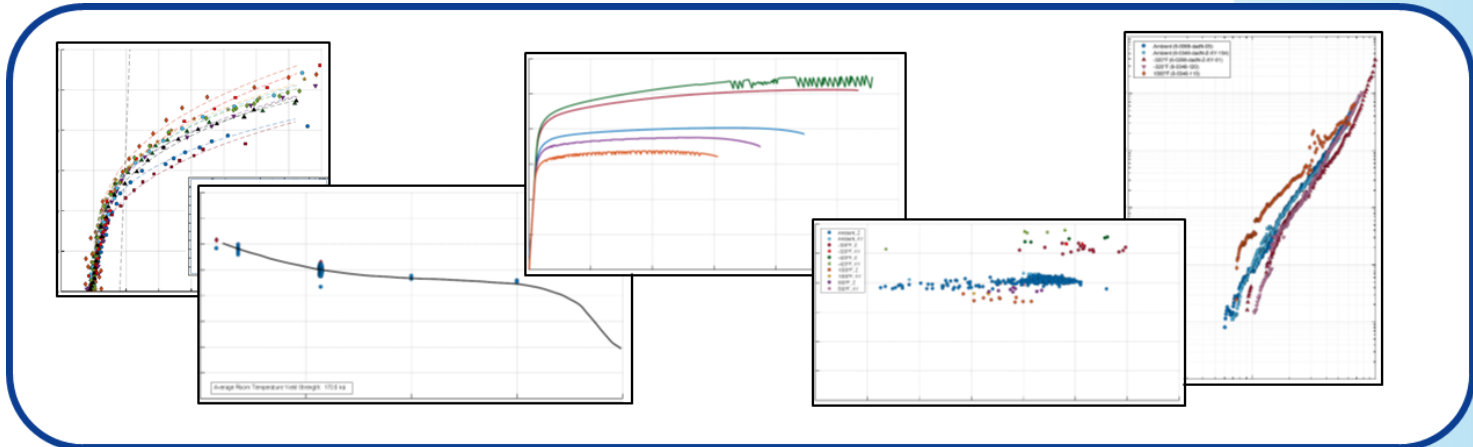
IN718 Microstructural Evolution



Key Quality Assurance Products



- Statistical Process Controls
- Acceptance Criteria
 - Derived from PCRD
 - Acceptance criteria for witness tests



Key Quality Assurance Products



- **Qualified Part Process (QPP)**
 - Pre-Production Article Evaluation
 - Powder removal, dimensions, surface quality, mechanical properties, internal quality, microstructure, high risk areas...
 - Additive Manufacturing Readiness Review
 - Stakeholder review of production engineering record, part drawing, approved PPP, Pre-Production Article Report...
 - If successful, ***AMRR demarcates when part process is qualified***
 - Complete part manufacturing process is locked for production
 - No changes without re-qualification or proper disposition
 - **QPP state is documented in the Quality Management System**
- **Production Engineering Controls**
- **Production Process Controls**
 - Manage and document Production

Key Quality Assurance Products



- **Acceptance Testing**

- **Witness Testing**

- [AMR-26] Witness sampling for each L-PBF build shall be described in the PPP, including sample types, designs, and quantities, their layout in the build volume, test methods, and acceptance criteria.

- Required for all builds, varies with Part Class
 - Differing Stand Alone versus Continuous Production criteria

- **NDE**

- [AMR-54] All L-PBF parts shall receive comprehensive NDE for surface and volumetric defects within the limitations of technique and part geometry unless otherwise substantiated as part of the Integrated Structural Integrity Rationale per section 6.1.4.

TABLE III. Witness specimen quantities for stand-alone acceptance

Class	Class							
	A1	A2	A3	A4	B1	B2	B3	B4
Tensile	6	6	6	6	6	6	6	6
FH Contingency	1	1	1	1	1	1	-	-
Metallography	2	2	1	1	1	1	-	-
Chemistry	1	1	-	-	-	-	-	-
HCF	2	2	2	2	2	-	-	-
Low Margin Point	A/R	A/R	-	-	-	-	-	-
Witness sub-article	A/R	-	A/R	-	A/R	-	-	-
Witness article	1 for 6	-	-	-	-	-	-	-
CQMP	A/R	A/R	A/R	A/R	A/R	A/R	-	-

Notes:

FH Contingency = Full-height contingency specimen

A/R = As required when specified in the PPP/QPP

Focus of next section: AM Defects and NDE

AM QA Opportunities



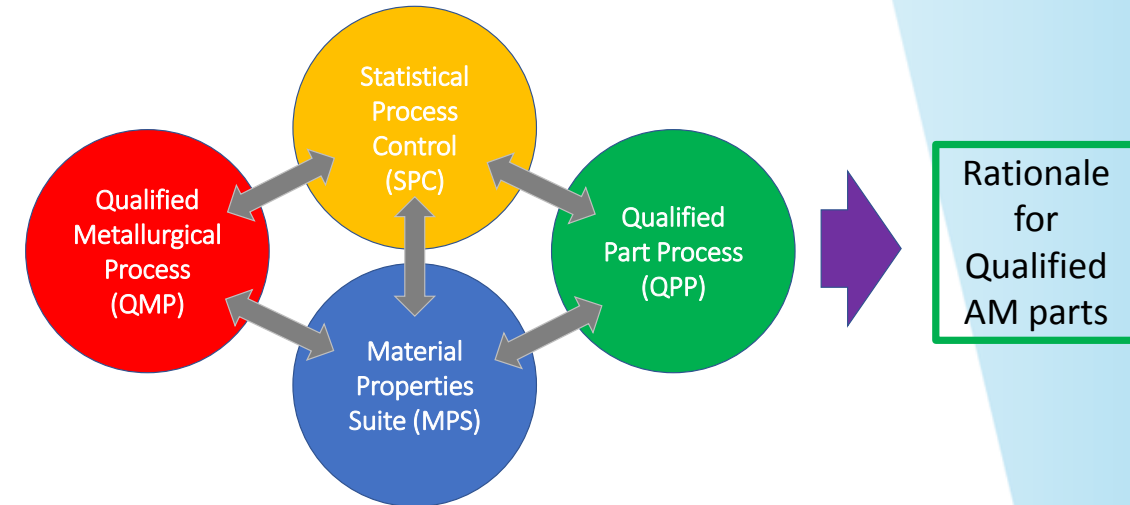
There are two primary opportunities to ensure AM reliability for qualification and certification rationale:

1. In-Process Controls (Control what you do)

- Qualify the AM Process and the AM Part Process
- Understanding fundamentals
 - Recognizing the process failure modes (pFMEA)
- Identifying observable metrics and witness capabilities
- Meticulous process scrutiny through SPC

2. Post-Process Evaluation (Evaluate what you get)

- Non-destructive Evaluation, Proof testing
- Post-build process monitoring data evidence



Part reliability rationale comes from the sum of both in-process and post-process controls, weakness in one must be compensated in the other

Nadcap® PBF QA Resources




Recently published:

AC7110/14 Audit Criteria for Laser and Electron Beam Metallic Powder Bed Additive Manufacturing

(Used as supplement to PRI AC7110)

- Good list of audit questions for suppliers
- Will not address all issues from MSFC-STD-3716, but provides excellent, detailed checklist and information.

 161 Thorn Hill Road Warrendale, PA 15086-7527	AUDIT CRITERIA	AC7110/14 REV. A Issue Date 12-2016 Revision Date 07-JUN-2018 Superseding AC7110/14 Rev. NA
Nadcap AUDIT CRITERIA FOR LASER AND ELECTRON BEAM METALLIC POWDER BED ADDITIVE MANUFACTURING		
TO BE USED ON AUDITS STARTING ON OR AFTER 09-SEP-2018		
1. SCOPE	This checklist is to be used as a supplement to PRI AC7110 for suppliers seeking laser and electron beam powder bed accreditation.	
2. GENERAL INFORMATION		
2.1 Additive Manufacture Scope	Processes performed at the facility (check appropriate boxes)	
	Baseline – Applicable to all processes/materials etc.	<input type="checkbox"/>
	Supplement A – Requirements for Pre-Heating in Powder Bed Machine	<input type="checkbox"/>
	Supplement B – Stress Relief Temperature Control	<input type="checkbox"/>
	Supplement C – Metallographic Evaluation of Qualification Parts	<input type="checkbox"/>
	Supplement D – Evaluation of Verification Specimens	<input type="checkbox"/>
2.2 Identify which process(es) are used	Laser beam metallic powder bed	<input type="checkbox"/>
	Electron beam metallic powder bed	<input type="checkbox"/>
3. REFERENCES		
3.1 Customer Specifications	Are applicable customer specifications available at the facility? YES NO	
<small>PRI operating procedures provide that "This report is published by PRI to advance the state of technical, engineering, and quality sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising there from, is the sole responsibility of the user"</small>		
<small>PRI values your input. To provide feedback on this document, please contact the appropriate commodity staff engineer. (Contact information is located at http://www.eaudit.net under "Contact Us") Copyright 2018 Performance Review Institute. All rights reserved. t-frm-15</small>		
<small>11-Jan-2018</small>		



WELD TASK GROUP Audit Handbook For AC7110/14

**AUDIT CRITERIA FOR LASER AND ELECTRON
BEAM METALLIC POWDER BED ADDITIVE
MANUFACTURING**

Released December 2016

Revised 15th Dec 2016

Revised March 2017

Revised June 2017

Revised June 2018 (for Rev A)

PERFORMANCE REVIEW INSTITUTE
161 THORN HILL ROAD
WARRENDALE, PA 15086-7527
724-772-1616

Section 4

Additive Manufacturing Defects And NDE Challenges



AM Defects: Effect of Process

- Certain AM flaws (for example, voids and porosity) can occur in most or all AM parts (non-process specific), and can be characterized using existing methods for welded or cast parts.
- Other AM flaws (for example layer, cross layer, unconsolidated and trapped powder) are unique to PBF and new or better NDE detection methods are needed.

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

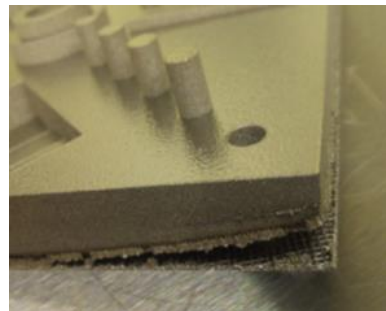
Develop new or better NDE methods

§ 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, unconsolidated powder is synonymous with lack of fusion (LOF) flaws

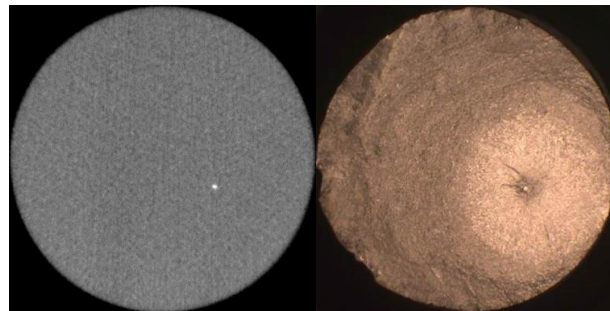


AM Defects

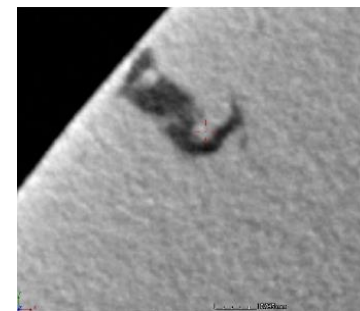
- **General PBF and DED defects** - interested in lack of dimensional accuracy or warping, inclusions, process-induced porosity, gas-induced porosity, and cracks (potential structural implications or out-of-tolerance part):



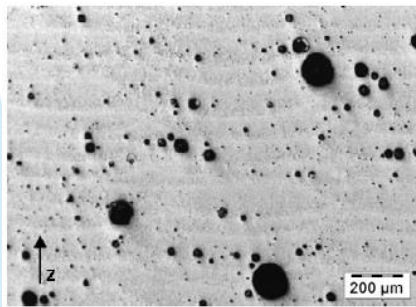
dimensions/warping



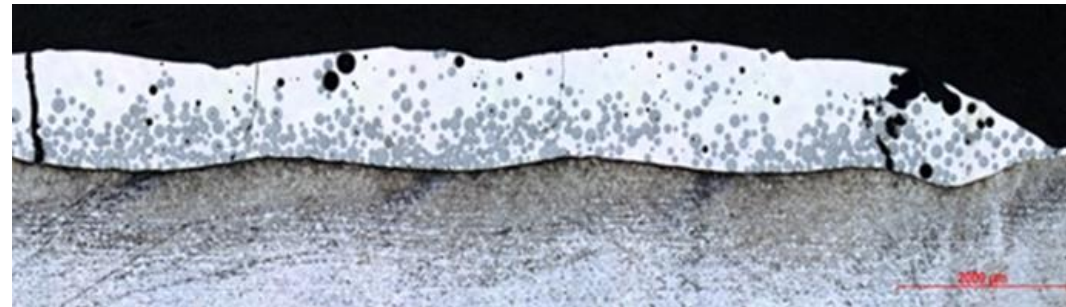
inclusions



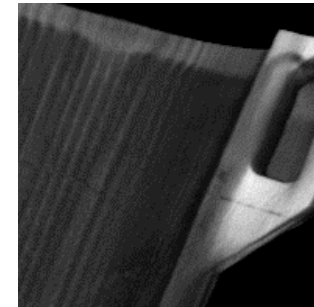
PBF process void



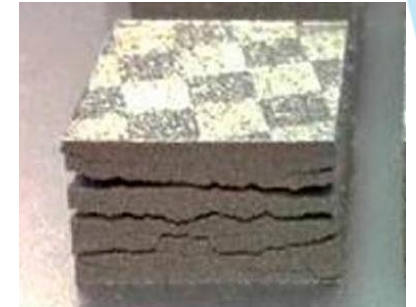
PBF gas porosity



DED gas porosity



PBF crack

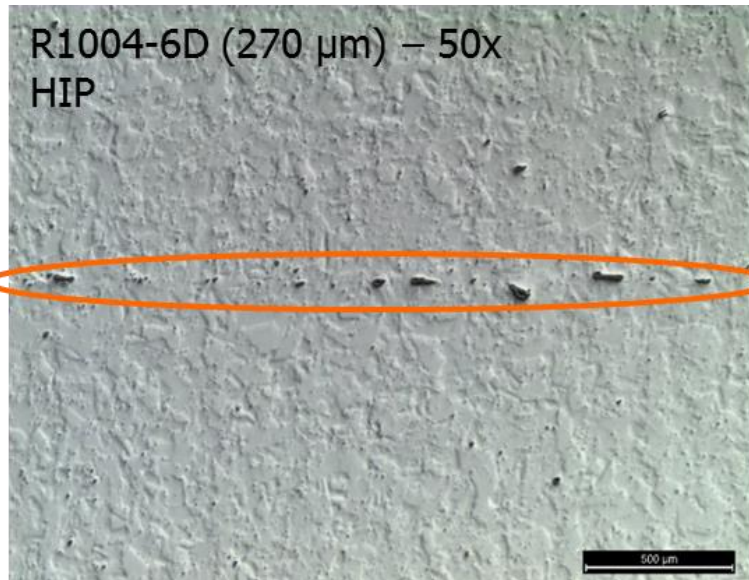


PBF delamination

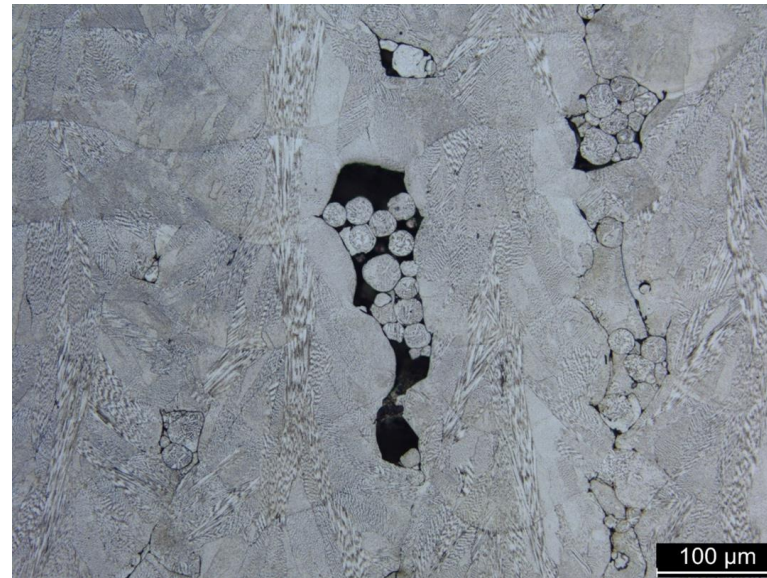


AM Defects

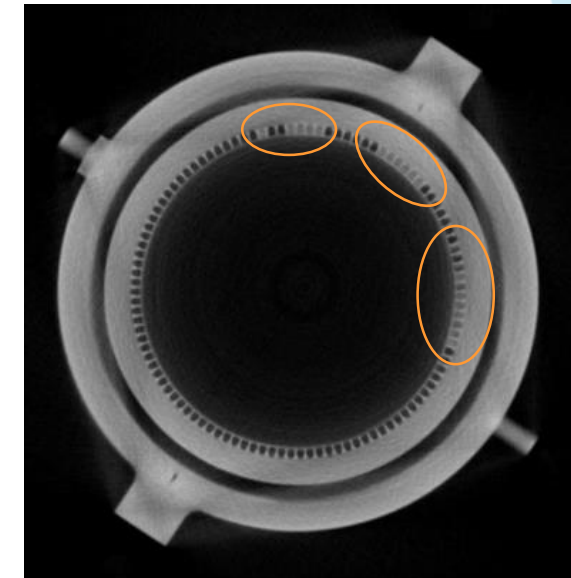
- **Specific PBF defects** – interested in skipped layer/stop-start flaws, lack of fusion (LOF), and trapped powder due to potential structural implications or out-of-tolerance part:



skipped layer/stop-start
(layer defect)



Vertical LOF
(cross layer defect)



trapped powder

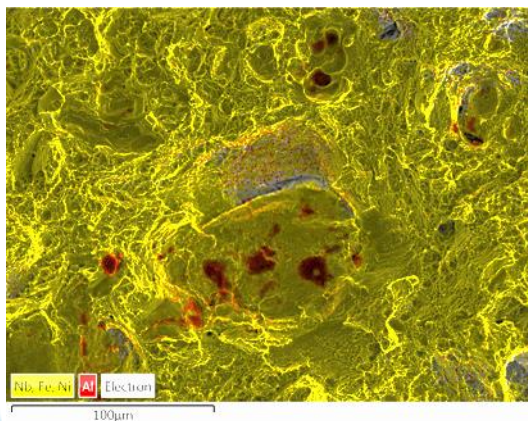


Bulk Defects Causing Mechanical Property Degradation

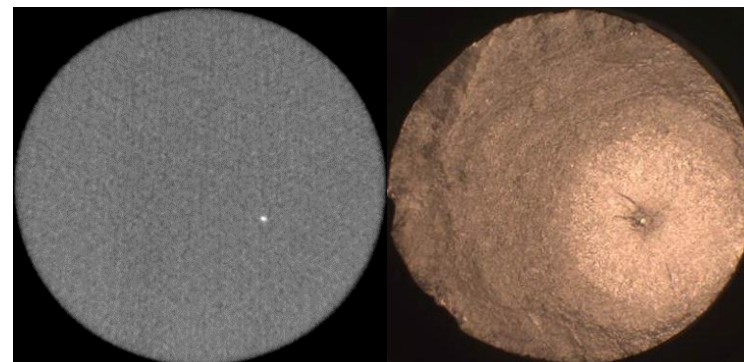
Inclusion – Foreign material either non-metallic or metallic incorporated into the deposited material. Inclusions are typically oxides, nitrides, hydrides, carbides, or a combination thereof and may or may not have some coherency with the surrounding material.

CAUSES – Formed due to contamination of the chamber gas, input material or dirty build chamber.

EFFECTS – Inclusions can serve as stress concentrators and the locus for catastrophic part failure (degraded mechanical properties).



Energy-dispersive x-ray spectroscopy (EDS) mapping of aluminum oxide inclusions in an UNS N07718 part (MSFC)

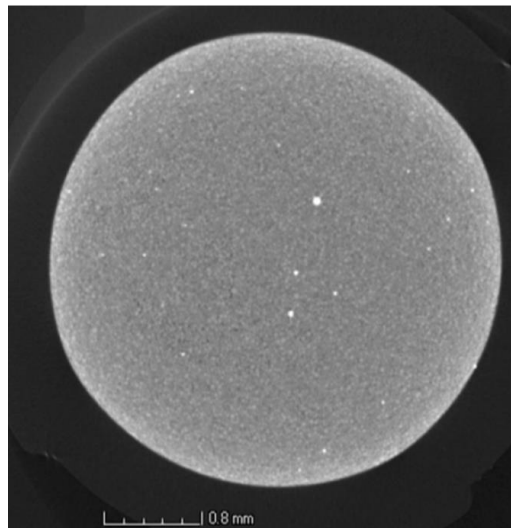


Micro-CT scan (left) and optical scan of fracture surface (right) of a Ti6-4 tensile specimen showing the locus of failure coinciding with an inclusion (MSFC)

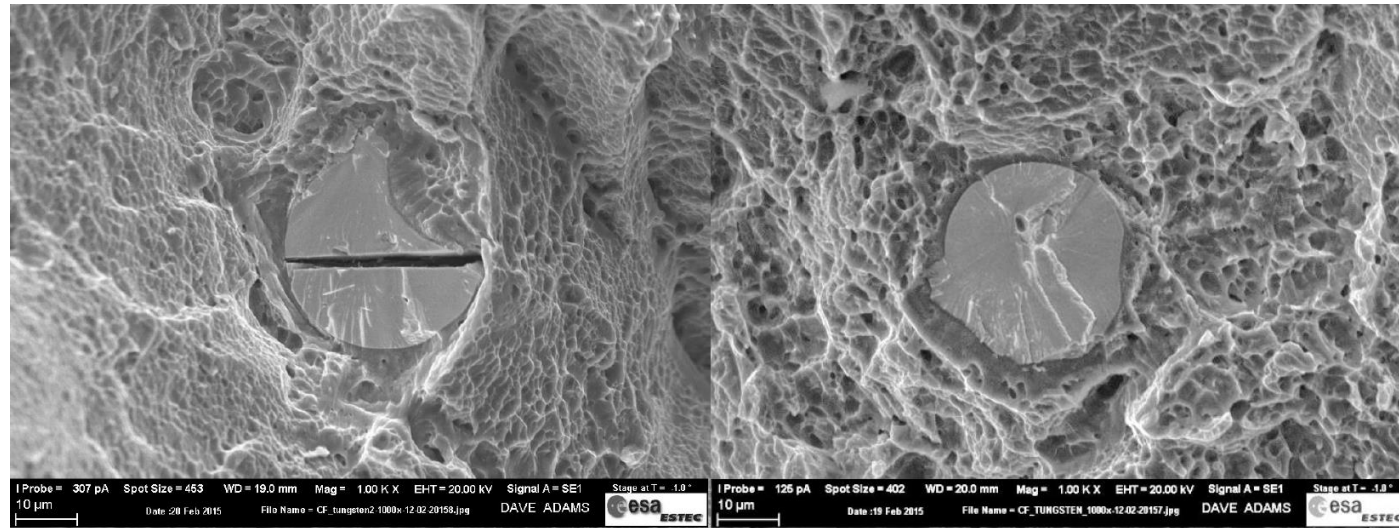


Inclusions

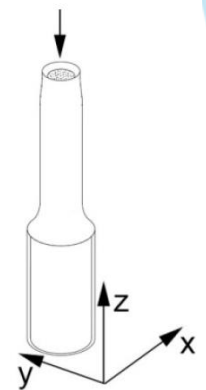
Powder characterization – ASTM F3049 defines feedstock characteristics which are considered useful to assure the confidence in the selected powder and in the final PBF part properties. Among those characteristics are the particle size and its distribution, the morphology (sphericity), the chemical composition, the flow characteristics, and the density of the powder. X-ray CT is used to characterize the defect population, namely inclusions.



X-ray CT slice image of the powder showing high density inclusions, visible as bright particles



SEM images of the fracture surface of a tensile specimen in the **Z** orientation showing close-up views of cracked inclusion (left) and an inclusion (right) with a brittle appearance.



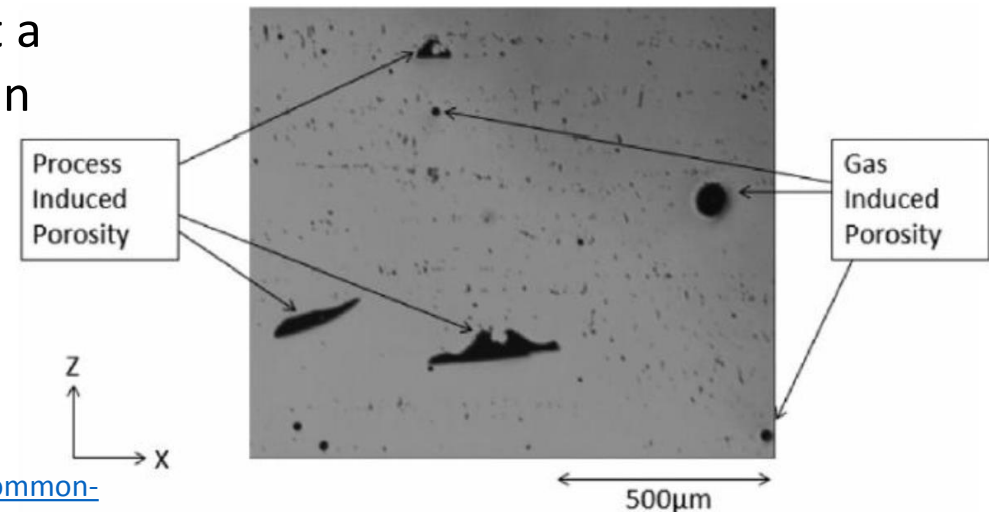


Bulk Defects with Variable Effects (may be significant or severe)

Void – A general term encompassing both irregularly-shaped or elongated cavities (process-induced porosity), and spherically-shaped cavities (gas-induced and keyhole porosity). These cavities can be empty (gas) or filled with partially or wholly unfused powder (LOF). Voids are distinct from intentionally added open cells to reduce weight.

CAUSES – See LOF, gas porosity, and keyhole porosity.

EFFECTS – Results in a less than fully dense part; at a sufficient quantity, size and distribution voids can degrade mechanical properties.



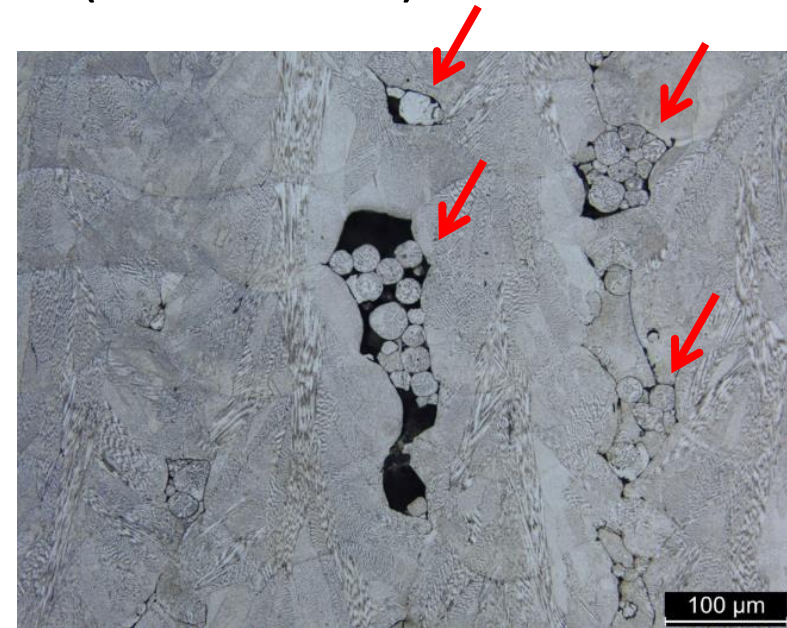


Bulk Defects with Variable Effects (may be significant or severe)

Lack of Fusion (LOF) – A type of process-induced porosity specific to unsintered (fully-melted) parts. Can be an empty cavity or contain unconsolidated powder. LOF typically occurs in the bulk, making its detection difficult. Like voids, LOF can occur across single (horizontal LOF) or multiple layers (vertical LOF).

CAUSES – 1) incomplete melting of a deposited layer onto a previously deposited solidified layer, 2) inadequate penetration of a deposited layer into the previous layer, 3) improper hatch spacing between two successive passes, or 4) "stop/start" process anomalies, caused by interruption of feedstock supply or short feed. 1) and 2) are caused by low power/fast scan rate settings.

EFFECTS – Like other forms of porosity and voids, LOF can cause a part to be less than fully dense, or degrade mechanical properties.



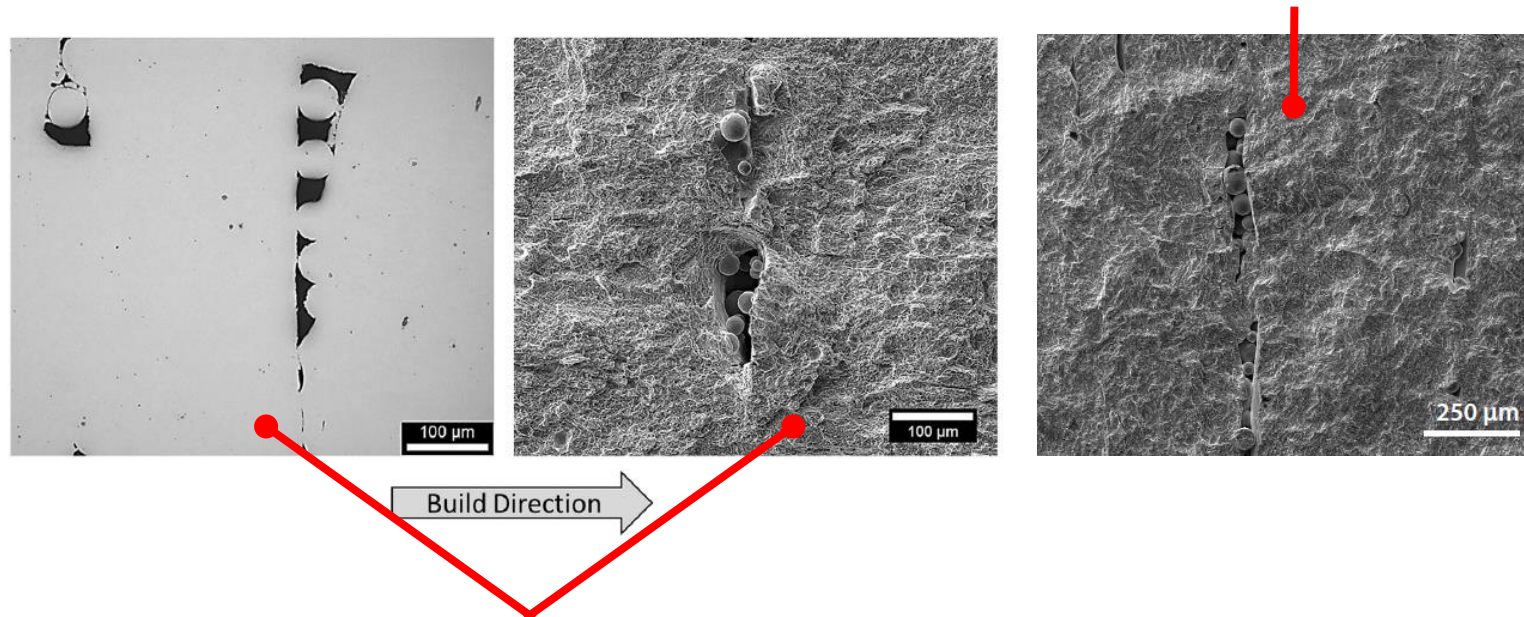
Vertical lack of fusion defects caused by hatch spacing set too wide (MSFC)



Lack of Fusion (LOF)

Defects (e.g., lack of fusion, voids) detected by micro-CT, need to be linked to probabilistic models for fracture, fatigue, and lifing predictions.

Fracture surface of as-built EBM Ti-6Al-4V tested in fatigue showing LoF defects perpendicular to the build direction



Metallographic cross-section and fracture surface of as-built EBM Ti-6Al-4V tested in fatigue

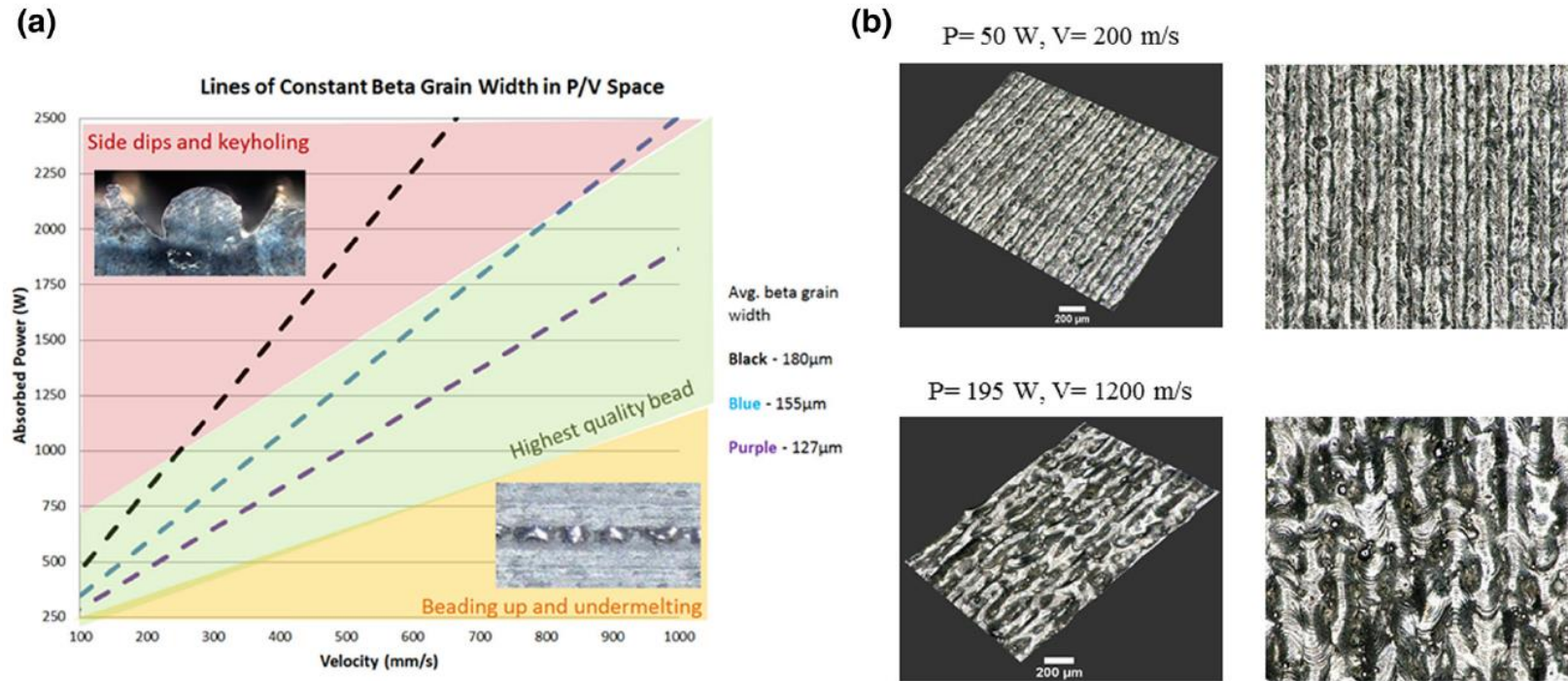
<https://link.springer.com/article/10.1007/s11837-015-1810-0>

<http://www.dtic.mil/dtic/tr/fulltext/u2/1035268.pdf>



Keyhole Porosity

Keyhole Porosity, grain size, and surface roughness are all correlated with laser or electron beam power and velocity:



(a) Power-Velocity (P–V) map for electron beam (Arcam) processed Ti-6Al-4V showing regimes of good quality beads as well as size of beta grains. (b) Inset shows different scales of surface roughness of multi-layer beads produced via laser-based techniques at different P–V combinations

<https://link.springer.com/article/10.1007/s11837-015-1810-0>

M. Seifi, D. Christiansen, J.L. Beuth, O. Harrysson, and J.J. Lewandowski, Ti-2015: The 13th World Conference on Titanium (Wiley, 2016).



AM Defects: Classes and Subclasses

TABLE 4.2 Additive Manufacturing Defect Classes and Subclasses^A

Defect Class	Defect Subclass
Surface	roughness, underfill, overfill, crater, stair stepping, worm track, contour separation
Porosity	spherical gas porosity, microporosity, void, surface breaking pores
Cracking	hot cracking, cold cracking, crater, cracking, HAZ as in DED to substrate, tearing
Lack of Fusion	cold lap, trapped powder, oxide lap, linear, planar, post HIP
Part Dimensions	external, internal, lattice, custom
Density	density, weight, volume, meets partial density spec
Inclusions	inclusions, segregation, banding, planar
Discoloration	oxidation
Residual Stress	reduced mechanical properties, out-of-tolerance dimensions
Hermetic Sealing	vacuum, pressure

^A Abbreviations used: --- = not applicable, DED = Directed Energy Deposition, HAZ = Heat Affected Zone, HIP = Hot Isostatic Pressing

[§] ASTM WK47031, new Draft Standard – Standard Guide for Nondestructive Testing of Metal Additively Manufactured Aerospace Parts After Build, ASTM International, West Conshohocken, PA (in ballot).

AM Defects: Effect on NDE Selection



TABLE 4.3 Application of NDT to Detect Additive Manufacturing Defect Classes^A

Defect Class	Covered in this Guide							Not covered in this Guide				
	CT/RT/ CR/DR	ET	MET ^B	PCRT	PT	TT	UT	AE	LT	ND	MT	VT
Surface	X ^C	X ^D	X	...	X ^D	...	...	...	...	...	...	X
Porosity	X	X ^D	...	X	X ^D	...	X	...	...	...	...	X ^E
Cracking	X	X ^D	...	X	X ^D	X	X	X	X ^F	...	X	X
Lack of Fusion	X	X ^D	...	X	X ^D	X	X	X	...	...	X	...
Part Dimensions	X	...	X	...	...	...	...	...	...	X ^G	...	...
Density ^H	X ^I	...	...	X	...	...	...	...	...	...	...	...
Inclusions	X ^J	X ^D	...	X	...	X	X	...	...	...	...	...
Discoloration	...	...	...	...	...	...	...	...	...	...	...	X
Residual Stress	...	X ^{D,K}	X	X	...	...	...	...	...	X	...	...
Hermetic Sealing	...	...	...	...	...	...	...	...	X ^F	...	...	...

^A Abbreviations used: ... = not applicable, Acoustic Emission, CR = Computed Radiology, CT, = Computed Tomography, Dr = Digital Radiology, ET = Eddy Current Testing, Leak Testing = LT, MET = Metrology, MT = Magnetic Particle Testing, ND = Neutron Diffraction, PCRT = Process Compensated Resonance Testing, PT = Penetrant Testing, RT = Radiographic Testing, TT = Thermographic Testing, UT = Ultrasonic Testing, VT = Visual Testing.

^B Includes Digital Imaging.

^C Especially helpful when characterizing internal passageways or cavities (complex geometry parts) for underfill and overfill, or other internal feature not accessible to MET, PT or VT (including borescopy).

^D Applicable if on surface.

^E Macroscopic cracks only.

^F If large enough to cause a leak or pressure drop across the part.

^G Conventional neutron radiography (NR) allows determination of internal and external dimensions.

^H Pycnometry (Archimedes principle).

^I Density variations will only show up imaged regions having equivalent thickness.

^J If inclusions are large enough and sufficient scattering contrast exists.

^K Residual stress can be assessed if resulting from surface post-processing (for example, peening).

[§] ASTM WK47031, new Draft Standard – Standard Guide for Nondestructive Testing of Metal Additively Manufactured Aerospace Parts After Build, ASTM International, West Conshohocken, PA (in balloting).

USAF/NDE of Complex AM Structures

AFRL-RX-WP-TR-2014-0162



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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UNITED STATES AIR FORCE

Contact: *Evgueni Todorov (EWI)*

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



Effect of AM Part Complexity on NDE

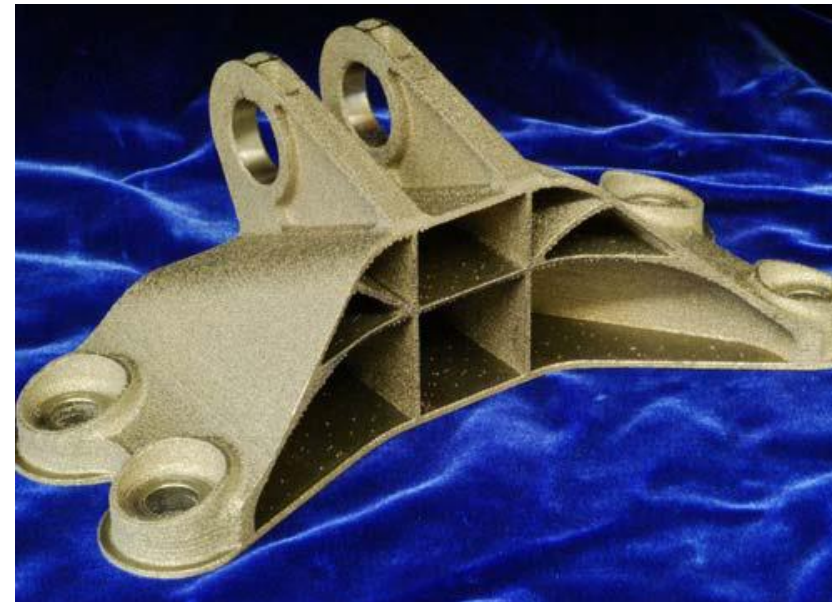
AFRL-RX-WP-TR-2014-0162

- Most NDE techniques can be used for Complexity Group[§] 1 (Simple Tools and Components) and Group 2 (Optimized Standard Parts):

1



2



[§] 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.



Effect of AM Part Complexity on NDE

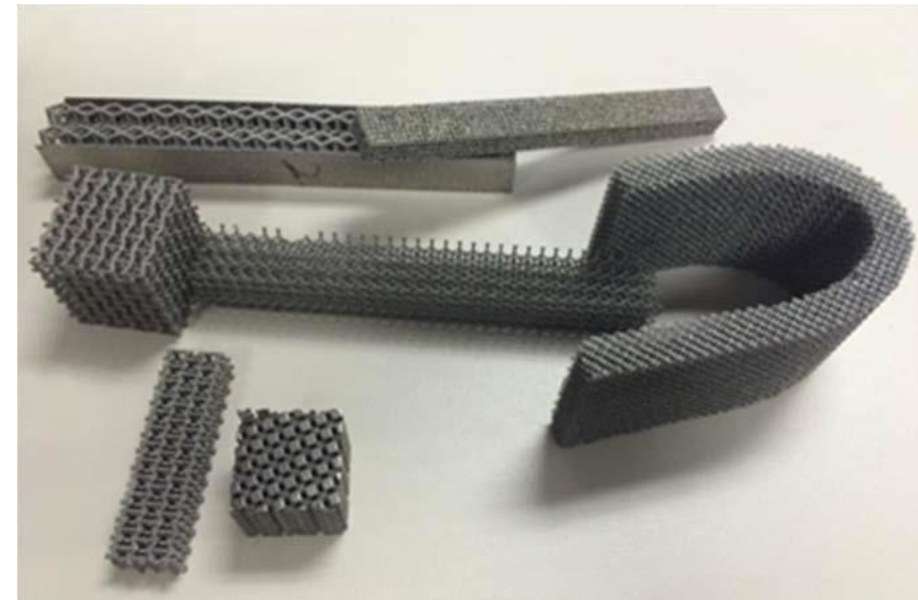
AFRL-RX-WP-TR-2014-0162

- Only PCRT, CT, and LT can be used for Complexity Group[§] 4 (Design-to-Constraint or Topology Optimized Parts) and Group 5 (Lattice Structures):

4



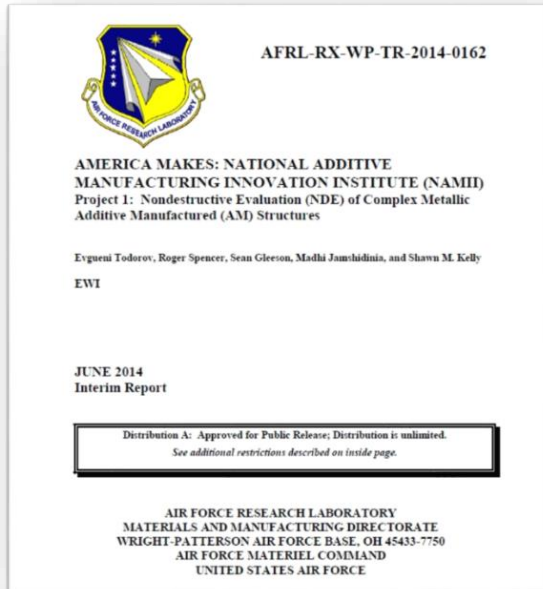
5



[§] 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.

Effect of AM Part Complexity on NDE

AFRL-RX-WP-TR-2014-0162



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	

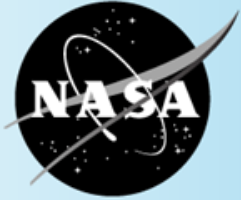
NDE options for design-to-constraint parts and lattice structures: PCRT, CT/ μ CT, and LT

Key:

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

Notes:

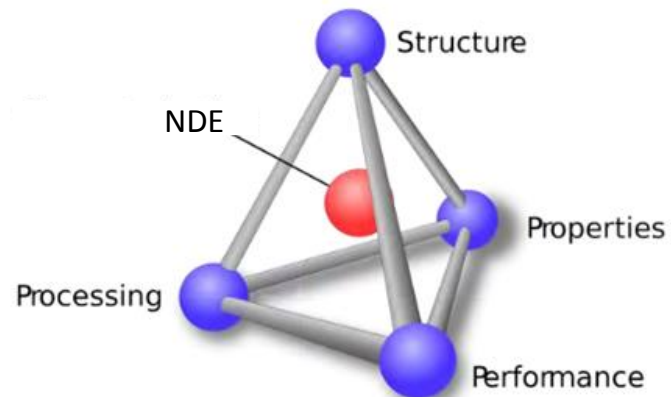
- (a) Only surfaces providing good access for application and cleaning
- (b) Areas where shadowing of acoustic beam is not an issue
- (c) External surfaces and internal surfaces where access through conduits or guides can be provided
- (d) Areas where large number of exposures/shots are not required



Main Findings

NASA/TM-2014-218560

- NDE identified as a **universal need spanning all aspects of additive manufacturing.**
- NDE identified as the **only effective way to ensure AM parts meet necessary NASA requirements.**
- NDE and materials experts **must develop techniques to characterize defects, determine their effect on performance, learn how to reliably detect them to screen for defects,** in order to qualify parts for use.





Top Level NDE Challenges

NASA/TM-2014-218560

- **Deeply embedded flaws** and **hidden internal features** can be difficult to detect or characterize or perform metrology on.
- **High part anisotropy** with 2D planar high aspect ratio (a/c (a is the *crack* depth and c is the half-surface length) defects perpendicular to Z-direction can be difficult to detect or characterize.
- **Rough as-built surfaces** interferes with surface-sensitive NDE method such as PT (penetrant testing) and ET (eddy current testing).
- Critical flaw types, sizes and distributions not defined for AM parts (**NDE accept/reject criteria are needed**).
- Lack of written procedures (**standards for NDE of AM hardware are needed**).

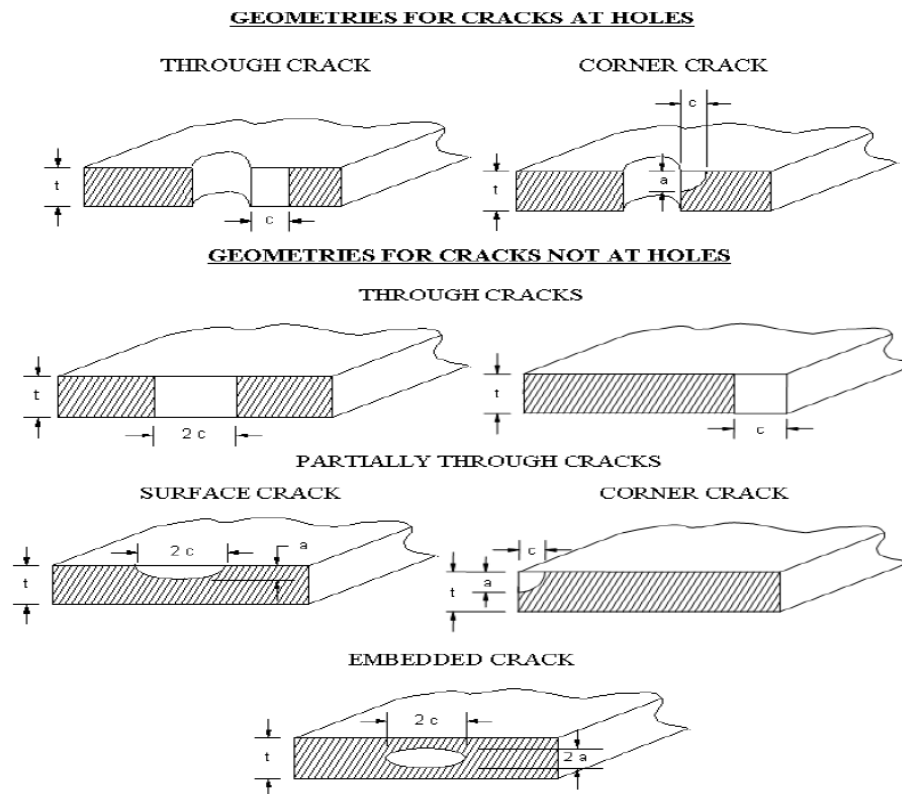


NASA-STD-5009 NDE Requirements

Fracture Critical Metal Hardware

- Must meet the NDE requirements given in NASA-STD-5009[§], but the 90/95 Probability of Detection (POD) crack sizes generally will be **inappropriate**:

NASA-STD-5009 crack geometries



- AM crack geometries
 - While diagram (left) can be used, do 5009 crack sizes (next slide) apply?
- What about other AM flaw types?
 - porosity/voids
 - V-LOF, H-LOF
 - gas
 - keyhole?
 - inclusions
 - surface roughness

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



NASA-STD-5009 NDE Requirements

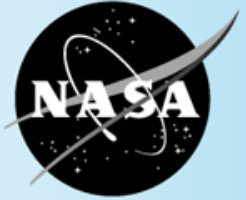
Fracture Critical Metal Hardware

- When considering cracks in AM parts, the NASA-STD-5009 crack sizes (right) will generally be **unsubstantiated or even inappropriate**.
- When considering pores and voids (non-crack flaws) in AM parts, other criteria in addition to flaw size must be considered:
 - Proximity to surface
 - Aspect ratio
 - N , number
 - Number of nearest neighbors
 - Distribution in regions of high design loads
 - Orientation relative to direction of principal stresses

Système International (SI) Units (millimeters)

Crack Location	Part Thickness, t	Crack Type	Crack Dimension, a^*	Crack Dimension, c^*
<u>Eddy Current NDE</u>				
Open Surface	$t \leq 1.27$	Through PTC ¹	t	1.27
	$t > 1.27$		0.51 1.27	2.54 1.27
Edge or Hole	$t \leq 1.91$	Through Corner	t	2.54
	$t > 1.91$		1.91	1.91
<u>Penetrant NDE</u>				
Open Surface	$t \leq 1.27$	Through Through PTC	t	2.54
	$1.27 < t < 1.91$		t	$3.81 - t$
	$t > 1.91$		0.64 1.91	3.18 1.91
Edge or Hole	$t \leq 2.54$	Through Corner	t	3.81
	$t > 2.54$		2.54	3.81
<u>Magnetic Particle NDE</u>				
Open Surface	$t \leq 1.91$	Through PTC	t	3.18
	$t > 1.91$		0.97 1.91	4.78 3.18
Edge or Hole	$t \leq 1.91$	Through Corner	t	6.35
	$t > 1.91$		1.91	6.35
<u>Radiographic NDE</u>				
Open Surface	$t \leq 2.72$ $t > 2.72$	PTC	$0.7t$	1.91
		PTC	$0.7t$	$0.7t$
		Embedded	$2a=0.7t$	$0.7t$
<u>Ultrasonic NDE</u> Comparable to a Class A Quality Level (ASTM-E-2375)				
Open Surface	$t \geq 2.54$	PTC	0.76	3.81
		Embedded**	1.65	1.65
			0.43	2.21
			0.99	0.99

Coming Reliance on In-Situ Monitoring



How to approach in-situ monitoring of AM processes?

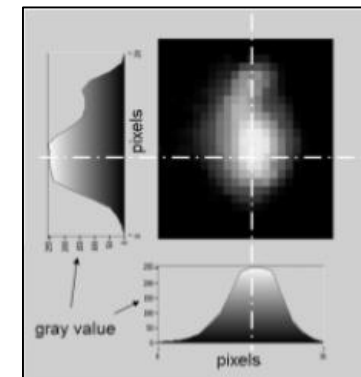
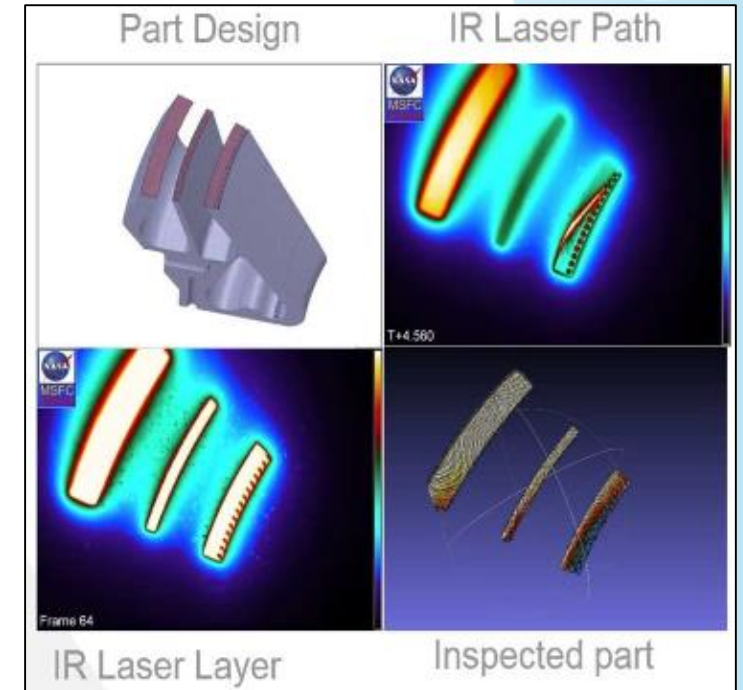
- Harnessing the technology is only half the battle
 - Detectors, data stream, data storage, computations
- Second half of the battle is quantifying in-situ process monitoring **reliability**

Community must realize that passive in-situ monitoring is an NDE technique

1. Understand physical basis for measured phenomena
2. Proven causal correlation from measured phenomena to a well-defined defect state
3. Proven level of reliability for detection of the defective process state
 - False negatives and false positives → understanding and balance is needed

Closed loop in-situ monitoring adds significantly to the reliability challenge

- No longer a NDE technique – may not be non-destructive
- Establishing the **reliability of the algorithm** used to interact and intervene in the AM process adds considerable complexity over passive systems



Concept Laser QM Meltpool

Wrap-Up / Recap



- Reinforced basic understanding of AM processes
- Familiarity with MSFC-STD-3716 requirements for metal spaceflight hardware
- Key Quality Assurance Products
 - Quality Management System, AS9100 (QMS)
 - Additive Manufacturing Control Plan (AMCP)
 - Equipment and Facility Control Plan (EFCP)
 - Training Plan/Program
 - Qualified Metallurgical Process Records (QMP)
 - Statistical Process Controls
 - Qualified Part Process (QPP)
 - Production Engineering Controls
 - Production Process Controls
 - Acceptance Testing
 - Witness Testing
 - NDE
- Learn about important AM defect types and how to detect them.
- Learn about the challenges and best practices for nondestructive evaluation (NDE) of metal AM parts.

End of Webinar

Questions?



Back-up Content

Additive Manufacturing Industry Standards

Why Standards?

OMB A-119

federal register

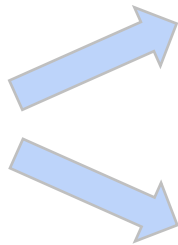
Thursday
February 19, 1998

Part IV

**Executive Office of
the President**

Office of Management and Budget

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



- Government agencies must consult with voluntary consensus organizations, and participate with such bodies in the development of standards when consultation and participation is in the public interest.
 - If development of a standard is impractical, the agency must develop an explanation of the reasons for impracticality and the steps necessary to overcome the impracticality.
 - Any standards developed must be necessarily non-duplicative and noncompetitive.
-
- NASA: improve mission reliability and safety
 - Industry: boost business and develop technology for American commerce

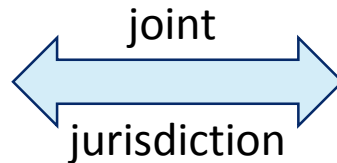




ASTM Standards, Active

Committee F42 on Additive Manufacturing Technologies

**ASTM
Committee F42**



**ISO
TC 261**



Test Methods (F41.01):

- [F2971-13 Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing](#)
- [F3122-14 Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes](#)
- [ISO/ASTM52921-13 Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies](#)

Design (F42.04):

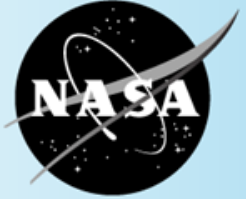
- [ISO/ASTM52915-16 Standard Specification for Additive Manufacturing File Format \(AMF\) Version 1.2](#)
- [ISO/ASTM52910-17 Standard Guidelines for Design for Additive Manufacturing](#)

Terminology (F42.91):

- [ISO/ASTM52900-15 Terminology for Additive Manufacturing – General Principles – Terminology](#)



right click
to open hyperlink



ASTM Standards, Active(cont.)

Committee F42 on Additive Manufacturing Technologies

Materials and Processes (F42.05):

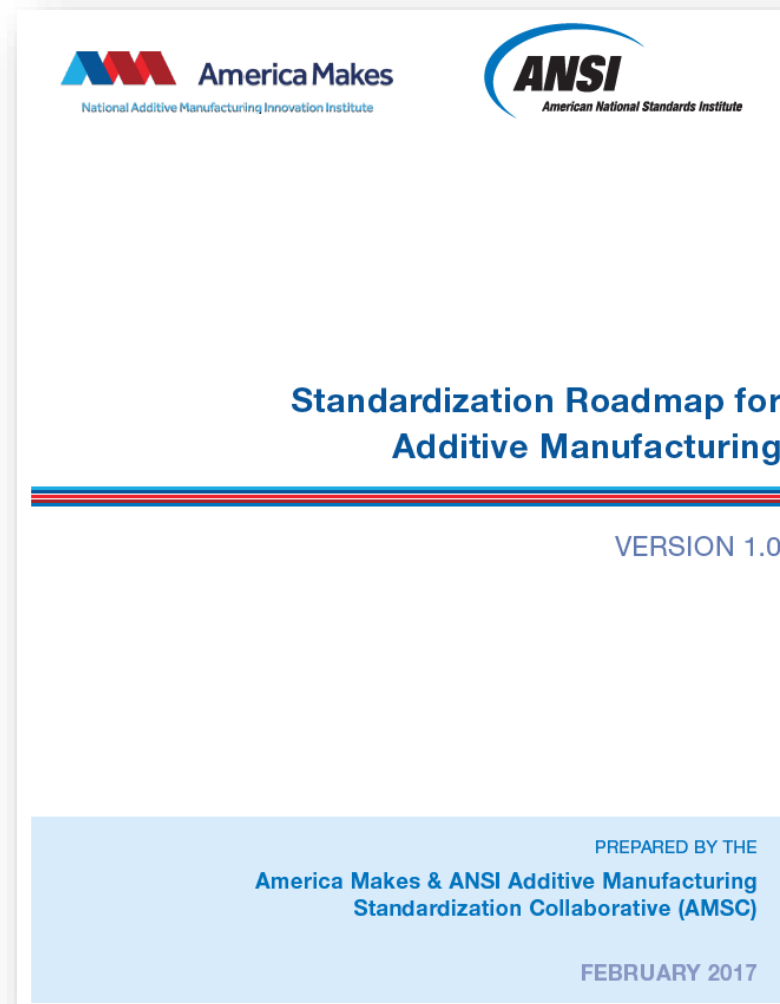
- [F2924-14 Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion](#)
- [F3001-14 Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI \(Extra Low Interstitial\) with Powder Bed Fusion](#)
- [F3049-14 Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes](#)
- [F3055-14a Specification for Additive Manufacturing Nickel Alloy \(UNS N07718\) with Powder Bed Fusion](#)
- [F3056-14e1 Specification for Additive Manufacturing Nickel Alloy \(UNS N06625\) with Powder Bed Fusion](#)
- [F3091/F3091M-14 Specification for Powder Bed Fusion of Plastic Materials](#)
- [F3184-16 Specification for Additive Manufacturing Stainless Steel Alloy \(UNS S31603\) with Powder Bed Fusion](#)
- [F3187-16 Guide for Directed Energy Deposition of Metals](#)
- [F3213-17 Finished Part Properties – Standard Specification for Cobalt-28 Chromium-6 Molybdenum via Powder Bed Fusion](#)
- [F3301-18 Post Processing Methods – Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion](#)
- [F3302-18 Finished Part Properties – Standard Specification for Titanium Alloys via Powder Bed Fusion](#)
- [ISO/ASTM52901-16 Guide for Additive Manufacturing – General Principles – Requirements for Purchased AM Parts](#)

Additive Manufacturing Standards

Additive Manufacturing Standardization Collaborative (AMSC)



- 89 standards gaps identified
 - 26 design gaps
 - 7 precursor materials gaps
 - 17 process control gaps
 - 6 post-processing gaps
 - 5 finished materials gaps
 - 5 NDE gaps
 - 15 Q&C gaps
 - 8 maintenance gaps
- Gaps were ranked low (19), medium (51), or high (19) priority depending on criticality, achievability, scope, and effect.



Additional Defect/NDE Content

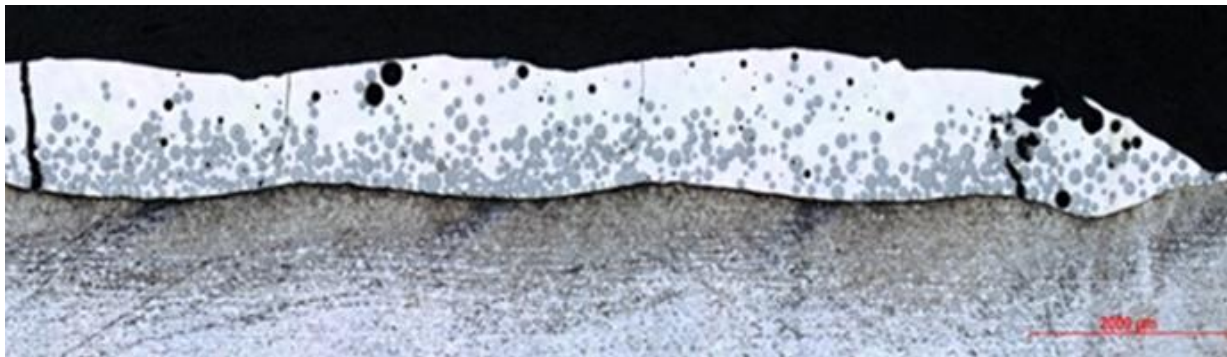


Bulk Defects with Variable Effects (may be significant or severe)

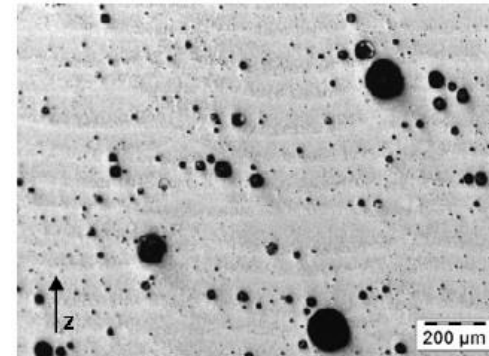
Porosity, Gas – Voids that are spherical or faceted in shape; with sufficient sources of gaseous species, may be intermittent within the deposit or elongated, interconnected, or chained due to the moving solidification front.

CAUSES – Absorption/desorption of gaseous species (nitrogen, oxygen) during solidification, or volatile contaminants (moisture or hydrocarbons) in the feedstock or fused part.

EFFECTS – If significant can cause a less than fully dense part, and/or cause in changes in material properties (modulus and Poisson's ratio), or fatigue life (near surfaces pores).



DED porosity (MTC)



PBF (SLM) porosity (Fraunhofer)

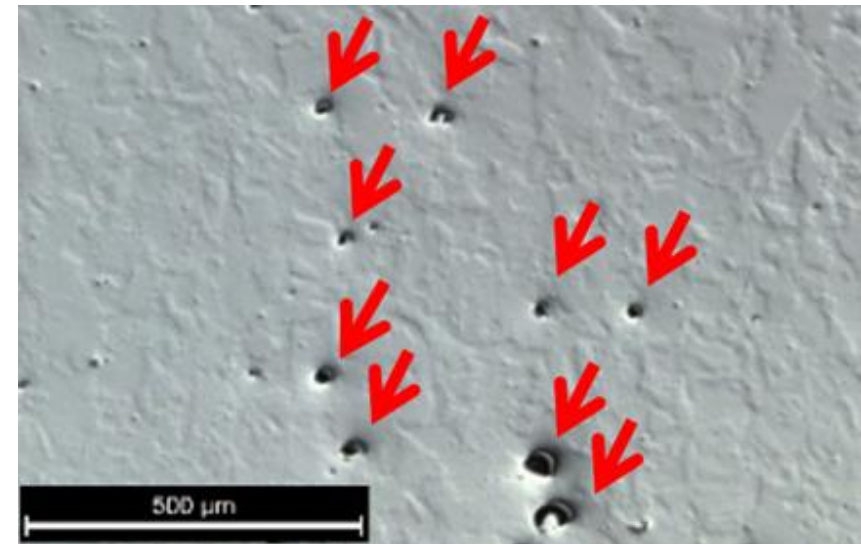
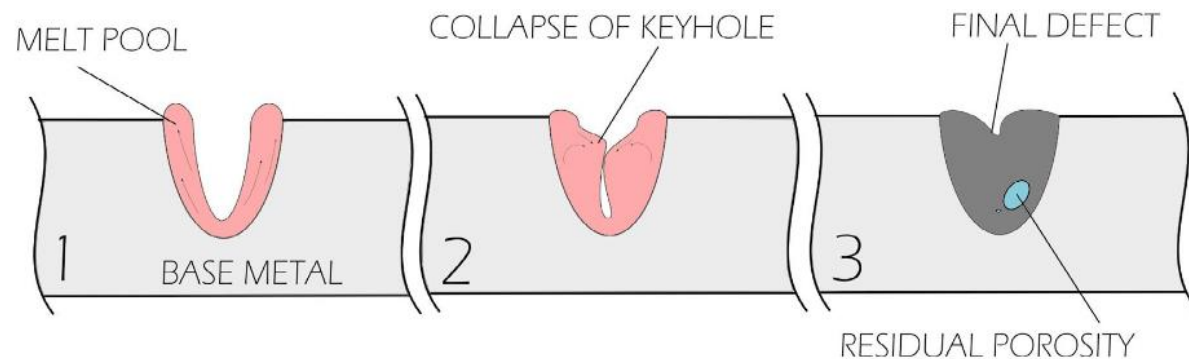


Bulk Defects with Little or No Effect

Keyhole Pore – A type of porosity characterized by a circular depression formed due to instability of the vapor cavity during processing.

CAUSE – Created when the energy density is sufficiently high to cause a deep melt pool resulting in hydrodynamic instability of the surrounding liquid metal and subsequent collapse, leaving a void at the root of the keyhole.

EFFECT – Minor or no observed effect on performance.



Keyhole pores in an as-built L-PBF part (MSFC)

https://www.researchgate.net/publication/259781021_A_two-dimensional_axially-symmetric_model_of_keyhole_and_melt_pool_dynamics_during_spot_laser_welding/figures?lo=1

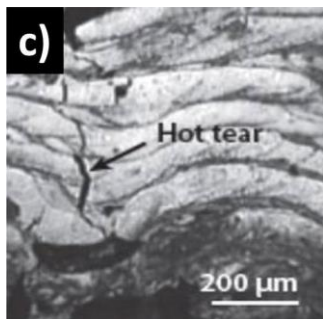


Bulk Defects with Unknown Effects (may be significant or severe)

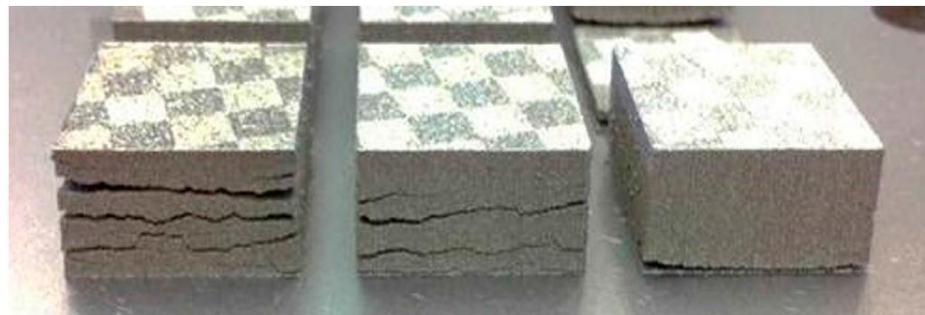
Crack – Separation of material which may be intergranular or transgranular in metals; in severe cases can result in 2-D (planar) separation (delamination) between adjacent build layers.

CAUSES – Temperature differences during fusing or sintering, and/or relief of residual stresses upon cooling.

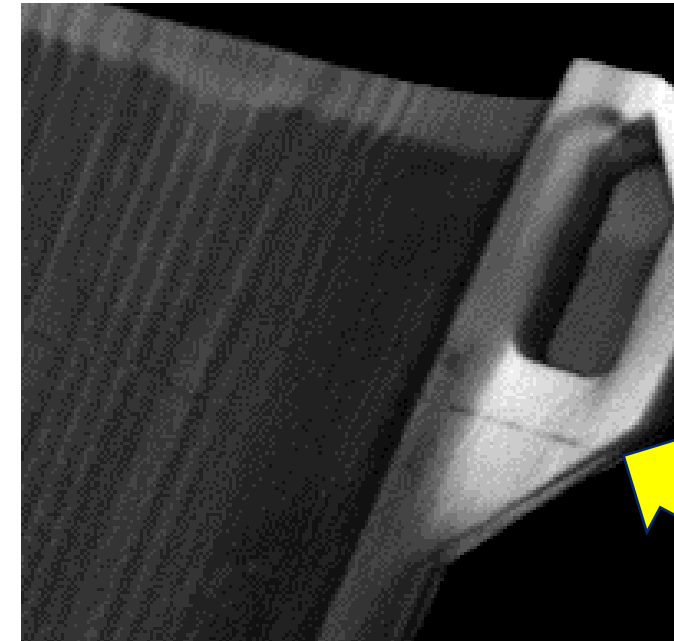
EFFECTS – Occurs as embedded or surface separation. Preferential propagation perpendicular to build axis (Z) can occur leading to delamination or layer separation.



Microscopic hot tear (NUAA)



Macroscopic delamination (University of Leuven)

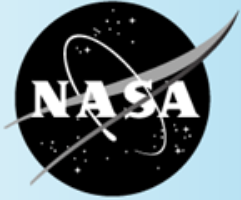


Crack in an L-PBF combustion chamber (computed tomogram, MSFC)

<http://manufacturingscience.asmedigitalcollection.asme.org/article.aspx?articleid=1903285>
<https://doi.org/10.1080/14686996.2017.1361305>

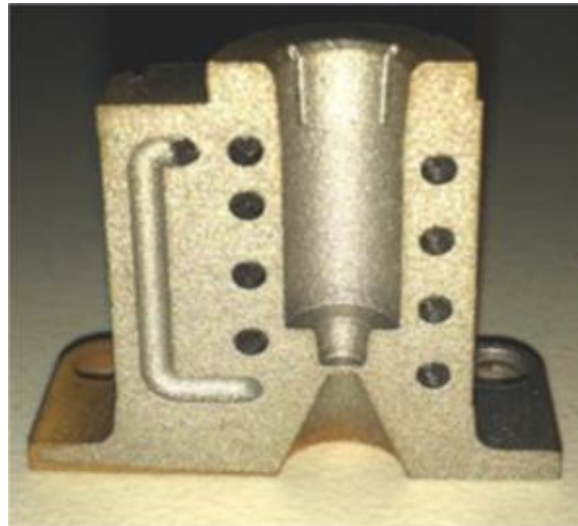
Effect of AM Part Complexity on NDE

AFRL-RX-WP-TR-2014-0162



- Some NDE techniques can be used for Complexity Group[§] 3 (Embedded Features):

3

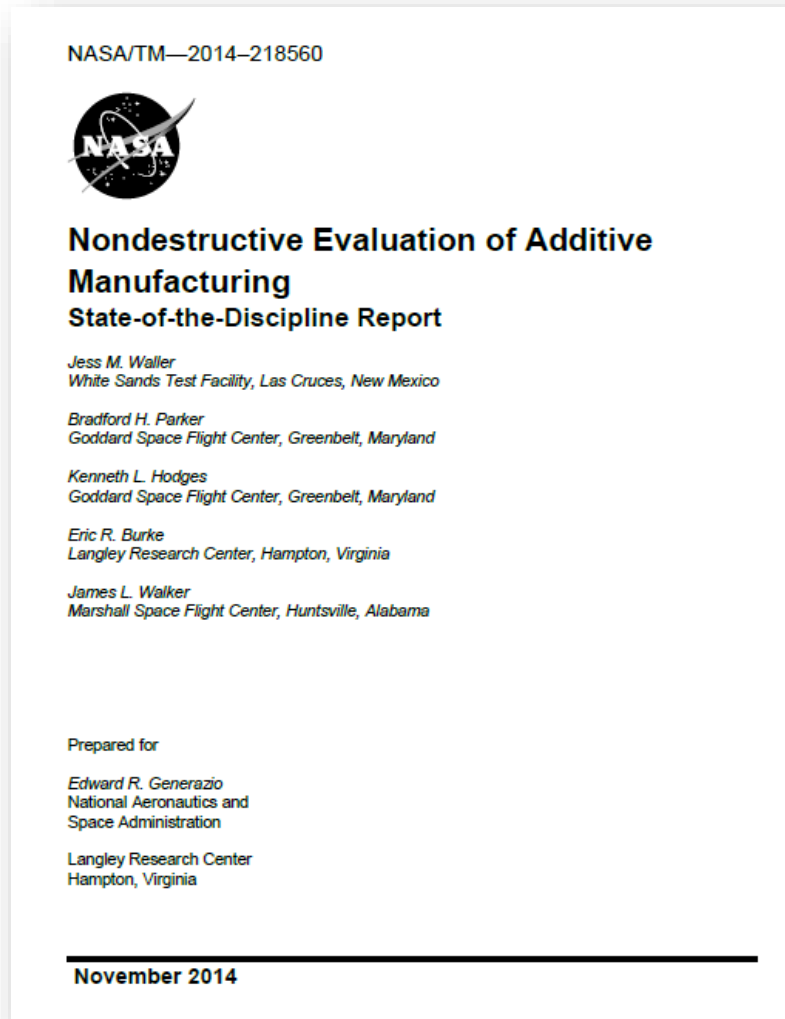
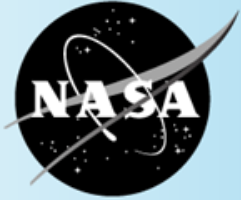


- Can be used: Process Compensated Resonance Testing (PCRT), Computed Tomography (CT), and Leak Testing (LT).
- Use is conditional: Eddy Current (ET), Penetrant Testing (Testing), Radiographic Testing (RT), Ultrasonic Testing (UT), Visual Testing (VT).

[§] 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.

NDE of AM Technology Gap Analysis

NASA/TM-2014-218560



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

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



Spaceflight Hardware

NDE Considerations

- **AM parts shall receive comprehensive NDE for volumetric and surface defects within the limitations of technique and part geometry.**
- 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), for example, 90/95, for fracture critical applications.
- NDE demonstration parts with simulated CIFS defects are used to demonstrate NDE detection capability.
- **Demonstration of adequate part life starting from NASA-STD-5009 flaw sizes is generally inappropriate for fracture critical, damage tolerant AM parts.**



Spaceflight Hardware

NDE Considerations

- For Class A parts, NDE indications of cracks, crack-like defects, or other findings of undetermined source should be elevated to senior review and disposition per applicable fracture control policy.
- Parts with high AM Risk may have regions inaccessible to NDE; understanding these risks requires identifying the inaccessible regions along with the CIFS.
- 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, ET, UT) may require the as-built surface to be improved for a successful inspection, depending on the defect sizes 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 standard defect classes for welds and castings welding or casting defect quality standards will generally not be applicable.**



Spaceflight Hardware

NDE Considerations

- Standards with NDE acceptance criteria for welding or casting quality are not considered applicable to L-PBF hardware.
- 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 be 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.**