Nondestructive Evaluation of Additive Manufacturing

State-of-the Discipline
Report

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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**.

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.

28 element Inconel 625 fuel injector built using SLM process

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.

Compared with a traditionally cast part, a printed [part] has superior strength, ductility, and fracture resistance, with a lower variability in materials properties.

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

Metallic Aerospace Components

GE will install 19 fuel nozzles into each 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.

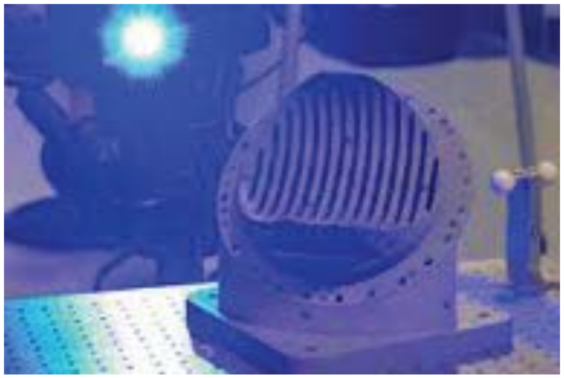
Simpler design – reduced the number of brazes and welds **from 25 to just five.**

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, GE Aviation and Sigma labs 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.

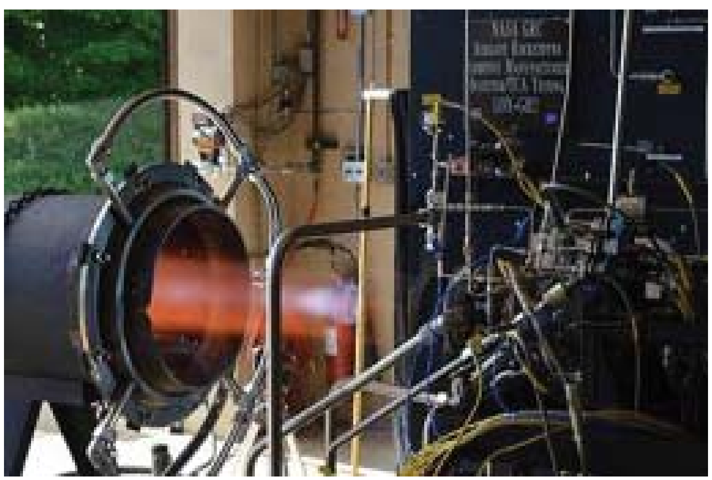
Agency Activity



Titanium 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

Key Players

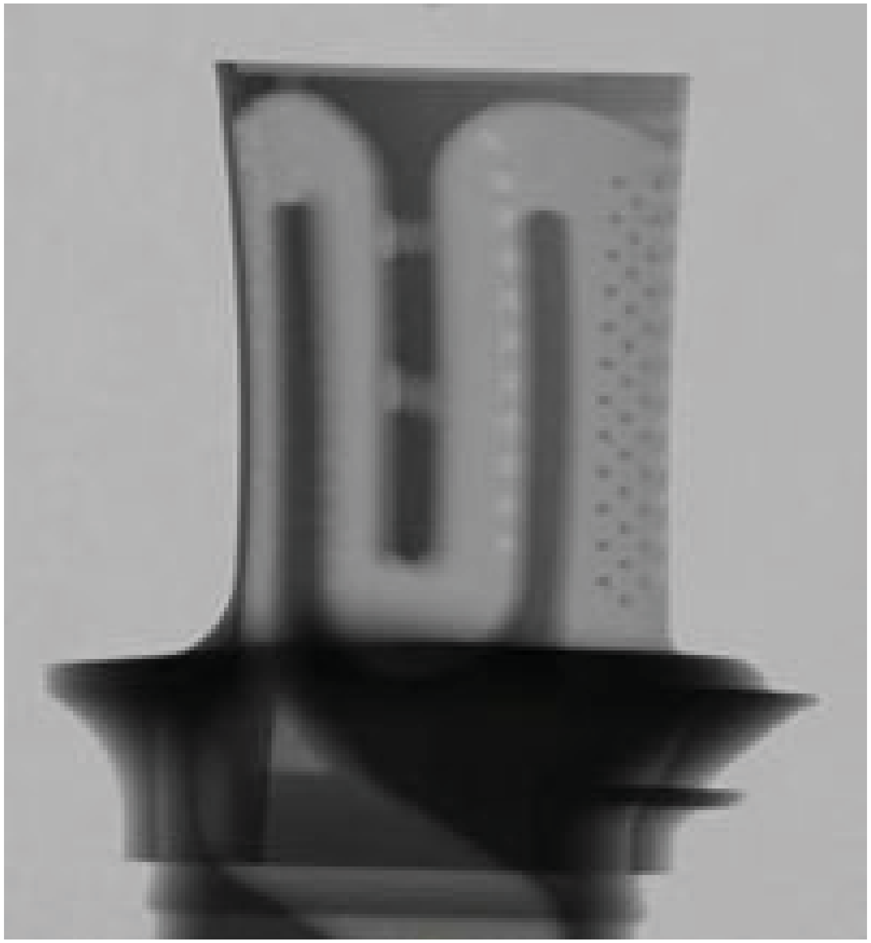
DOD, Manufacturing Demonstration Facility, Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D) at Penn State University
www.cimp-3d.org/

DOE, Oak Ridge National Laboratory, Manufacturing Demonstration Facility
www.ornl.gov/user-facilities/mdf

NAMMI/America Makes americamakes.us

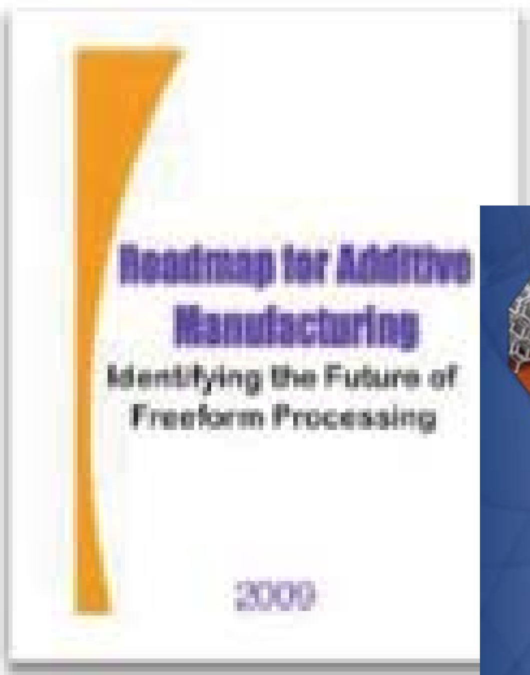
EU AMAZE (Additive Manufacturing Aiming Toward Zero Waste and Efficient Production)
www.amaze-project.eu

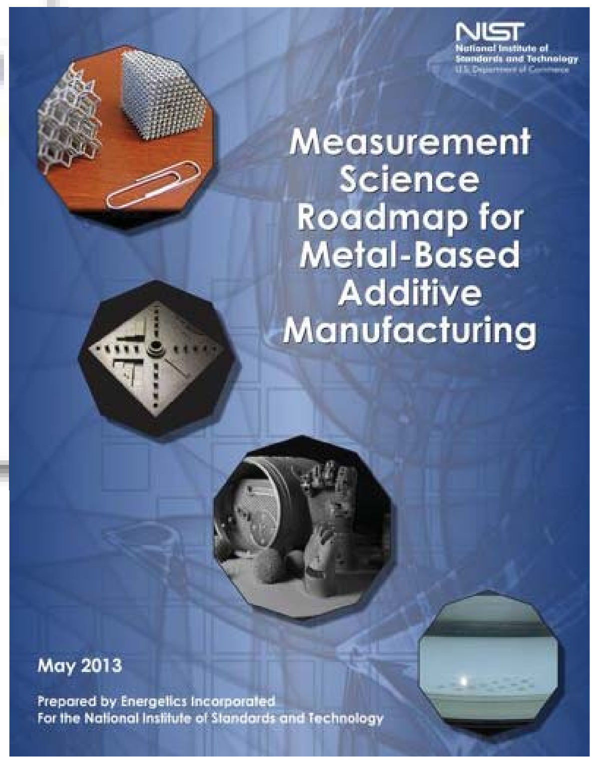
NIST Measurement Science for Additive Manufacturing Program
www.nist.gov/el/isd/sbm/msam.cfm



Neutron radiograph of an Inconel 718 turbine blade fabricated using DLMS

Gap Analysis: NIST Roadmap





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NIST Roadmap

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

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-situ Process Monitoring. 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

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 tailored for AM processes
- Lack of probability of detection (POD) data
- Lack of mature In process monitoring techniques

Agency CT Assets

CT System Specification	GSFC
CT System Vendor	North Star Imaging
CT System Model	X5000CT custom
Detector Vendor/Model	Dexela 7529
Detector Type (digital flat panel/linear array/intensifier screen)	Digital flat panel (CMOS)
Detector Size (mm x mm)	230 x 290
Detector Size (pixels x pixels)	3888 x 3072
Detector Pitch (microns)	75
Detector Bit Depth	14-bit
X-ray Tube Vendor/Model	Yxlon FXE-225.99 Dual Head
X-ray Beam Class (minifocus/microfocus/nanofocus)	Microfocus
X-ray Beam Shape (fan/cone/other)	Cone beam
X-ray Tube Type (closed/open)	Open
X-ray Peak Voltage (kV)	225
X-ray Peak Amperage (A)	3 (dir), 1 (trans)
X-ray Peak Power (W)	280 (dir), 10 (trans)
Minimum Spot Size (microns)	6 (dir), 2 (trans)
Specimen Table Capacity (kg)	45
Motion, Degrees of Freedom (# of trans/rot axes)	7
Reconstruction Computing Structure (CPU/GPU/Other)	GPU
Partial Angle Scan Capability (Yes/No)	Yes
Helical Scan Capability (Yes/No)	Yes
Scan Volume Stitching Capability (Yes/No)	No
Time Domain Scanning Capability/4D CT (Yes/No)	No

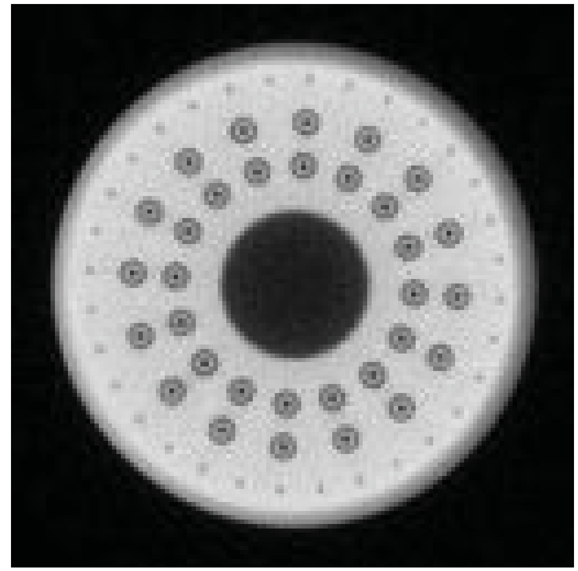
Agency CT Assets

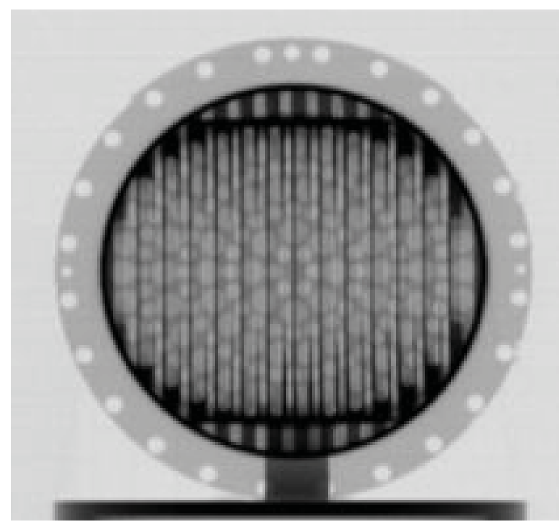
CT System Specification	GSFC	GRC	KSC	JSC	JSC	LaRC	MSFC
Detector Type	a-Si	a-Si	a-Si	a-Si	a-Si	a-Si	CdWO4
Detector Size (mm x mm)	230 x 290	230 x 290	195 x 244	400 x 400	400 x 400	400 x 400	
Detector Pitch (microns)	75	75	127	200	200	200	
Minimum Spot Size	6 um	6 um	6 um	7 um	400 um	6 um	2000 um
X-ray Peak Voltage (kV)	225	225	225	150	450	225	2000

- As pixel size decreases detector size decreases: inspection volume decreases
- As x-ray energy increases spot size increases: resolution decreases

CT Limitations

- Not reliable for crack detection
- Trade-off between part size and sensitivity
- Time consuming data acquisition
- Time consuming data analysis
- Lack of POD data





Certification

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

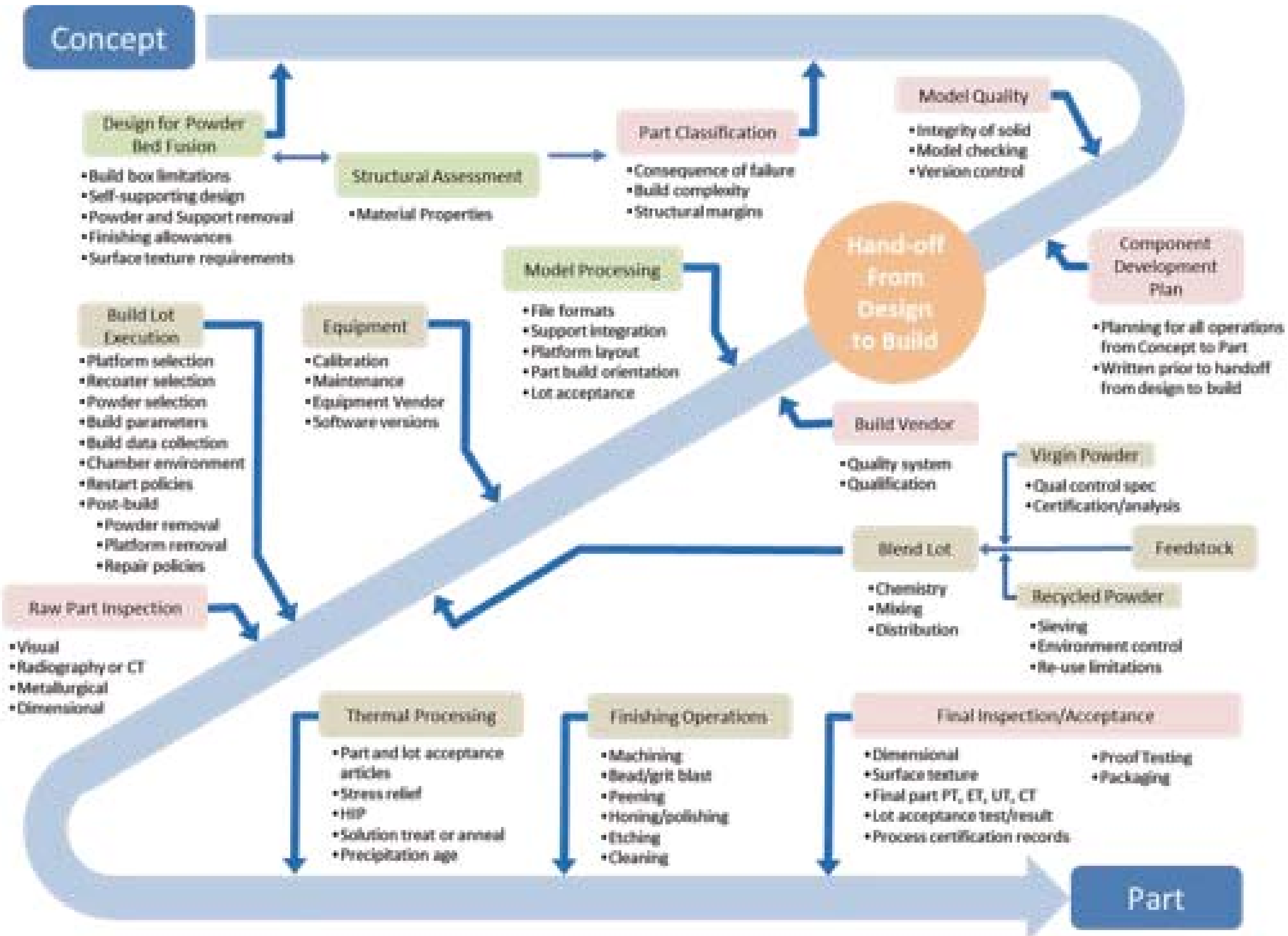
Certification is the affirmation by the program, project, or other reviewing authority that the verification and validation process is complete and has adequately assured the design and as-built hardware meet the established requirements to safely and reliably complete the intended mission.

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



OSMA NDE Program Funding

The NDE of AM task was divided into five subtasks designed to take advantage of the NDE expertise across the agency and to address the three most common metallic AM processes: Direct Laser Sintering (DLS), Electron Beam Melting (EBM) and Electron Beam Freeform Fabrication (EBF^3). The DLS and EBM subtasks will address Inconel and Titanium alloys commonly used in propulsion components and the EBF^3 subtask will address Titanium used in structural applications. The NDE modeling and the development of consensus standards subtasks will address all AM processes and materials.

An Assessment of NDE Capability and Materials Characterization for Complex Additive Manufacturing Aerospace Components: MSFC and GRC

Fundamental Methodology for Additive Manufacturing via NDE Modeling: LaRC

Investigation of NDE Flaw Detectability AM Parts: JSC and LaRC

Titanium Powder Additive Manufacturing Non-Destructive Evaluation: KSC

Development of NDE of Additive Manufactured Parts Voluntary Consensus Organization Standards:
WSTF

Development of X-ray Computed Tomography Performance Standards: GSFC