Summary of NDE of Additive Manufacturing Efforts in NASA

Jess Waller and Regor Saulsberry
NASA White Sands Test Facility
Bradford Parker and Kenneth Hodges
NASA Goddard Space Flight Center
Eric Burke and Karen Taminger
NASA Langley Research Center

qnde
Review of Progress in Quantitative Nondestructive Evaluation

SESSION 5, ADDITIVE MANUFACTURING I

Boise, ID

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1:30 – 2:10 PM MDT (GMT-7 hr)

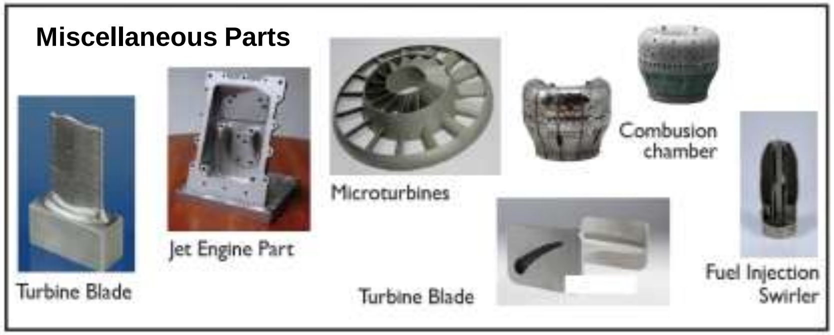
Introduction

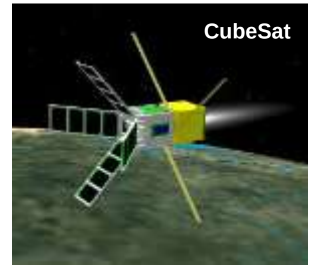
- General Rationale for Additive Manufacturing (AM)
  - Operate under a 'design-to-constraint' paradigm; make parts too complicated to fabricate otherwise
  - Reduce weight by 20 percent with monolithic parts
  - Reduce waste (green manufacturing)
  - Eliminate reliance on Original Equipment Manufacturers for critical spares
  - Extend life of in-service parts by innovative repair methods
- NASA OSMA NDE of AM State-of-the-Discipline Report
- Overview of NASA AM Efforts at Various Centers
  - Analytical Tools
  - Ground-Based Fabrication
  - Space-Based Fabrication
  - Center Activity Summaries
- Overview of NASA NDE data to date on AM parts
- Gap Analysis/Recommendations for NDE of AM

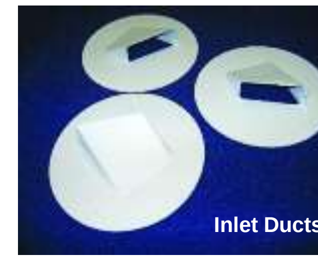
Rationale for Additive Manufacturing in Space

Current Manufacturing Approach	Additive Manufacturing Approach
Dependent on Earth Space missions are isolated in distance and time, yet completely dependent on Earth	***Independence from Earth*** All space missions can manufacture parts, tools and eventually structures in space
Cannot Build Large Structures All equipment must fit inside launch vehicle, limiting size of structure	***Build Large Structures*** All delicate, large structures that cannot be launched or build on Earth
Extreme Over-Planning Missions must plan for every 'what if' scenario and have multi-redundancy	***On-Demand Manufacturing*** Build only what is needed on-demand. Bring only input material and 3D printer
No Emergency Solution In case of emergency, astronauts must 'jerry rig' a solution or face loss of mission or worse	***Time-Sensitive Emergency Solutions*** In case of an emergency, design and print the exact parts needed immediately
Built for Launch Over-manufactured satellites, spacecraft and structures are built to survive launch forces	***Built & Optimized for Space*** Build satellites, spacecraft and structures to be optimized for space, not launch

Aerospace Industry AM Examples







- **GE** – Titanium fuel injector for LEAP™ engine
- **EADS** – Airbus A320 nacelle hinge brackets
- **Boeing** – Plastic inlet ducts for high-altitude aircraft
- **SpaceX** – Inconel®[1] direct metal laser sintered SuperDraco rocket engine combustion chambers
- **CRP Technology** – CubeSat with integrated Micro-Electro-Mechanical System (MEMS) propulsion
- **Aerojet Rocketdyne** – Entirely 3D-Printed “Baby Bantam” liquid rocket demonstration engine
- **Northrop Grumman** – One-piece EBM Ti-6Al-4V UCAV warm air mixer

NASA, the Federal Aviation Administration, the Department of Defense and others are gradually approaching how to certify additively manufactured aerospace parts for critical structures

[1] Inconel® is a family of austenitic nickel-chromium-based superalloys and a registered trademark of Precision Castparts Corp., Portland, OR 97239.

Background

- NASA has an opportunity to push the envelope on how AM is used in zero gravity to enable in-space manufacturing of flight spares and replacement hardware crucial for long-duration, manned missions.

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

Background (cont.)

- The impact of NDE on AM is cross-cutting and spans materials, processing, quality assurance, testing and modeling disciplines. Appropriate NDE methods are needed before, during, and after the AM production process.
- Adoption of AM parts is slow because of ambiguity in current validation and verification approaches, which are intimately tied to NDE capability.
- A key barrier for AM processes and equipment is that existing NDE methods and techniques are not optimized for AM processes, materials, or parts. Techniques are either non-existent or lacking for in-situ process NDE and post-process NDE of finished AM parts using conventional NDE techniques is challenging or still emerging.§

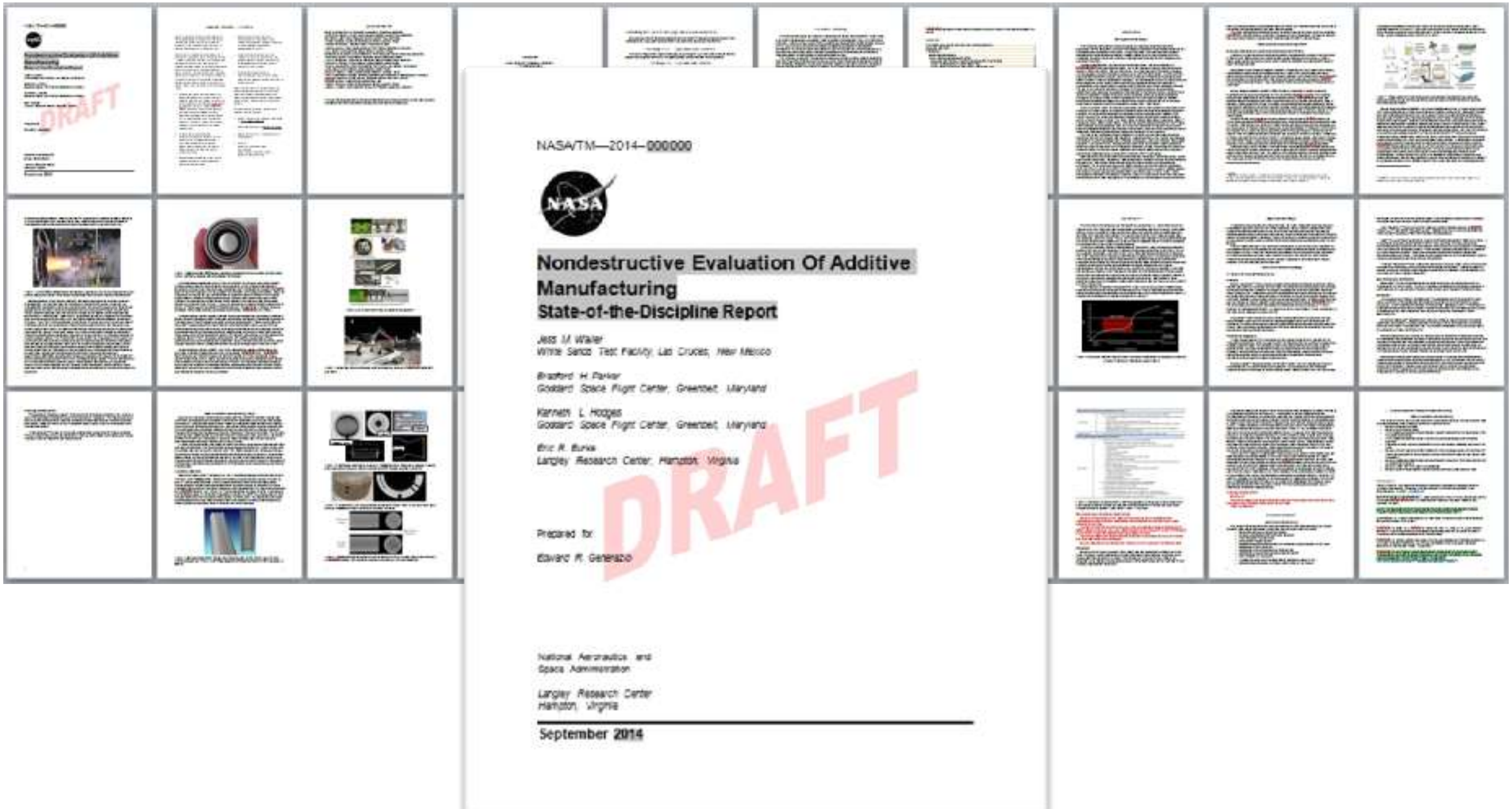
§ National Institute of Standards and Technology, *Measurement Science Roadmap for Metal-Based Additive Manufacturing*, prepared by Energetics Incorporated, Columbia, Maryland, for NIST, U.S. Department of Commerce, May 2013, p. 19.

NASA NDE Working Group
NDE of AM
State-of-the-Discipline Report

Status: NDE of Additive Manufacturing State-of-Discipline Report

1) NASA has begun putting together a "State-of-the-Discipline" report on additive manufacturing with an emphasis on the NDE needed, and follow-on recommendations on related NDE development and standards within NASA.
2) An annual National Science and Technology Council NDE Communication Group Meeting was held in Nov. 2013 in Arlington, VA with twelve NDE leaders from U.S. government agencies. Additive manufacturing was among the topics discussed; however, the group was not ready to join with NASA in developing a "State-of-Discipline" report focusing on the NDE needed. After such a report is completed in Sept. 2014, and a more structured discussion is held, increased synergy between NASA and other government agencies may be possible.

Status: NDE of Additive Manufacturing State-of-Discipline Report



Industry, government and academia is being actively solicited to share their NDE experience relevant to AM in this report

NASA AM Activities

NASA Activities in Additive Manufacturing

NASA's additive manufacturing effort can be broken down into three main areas:

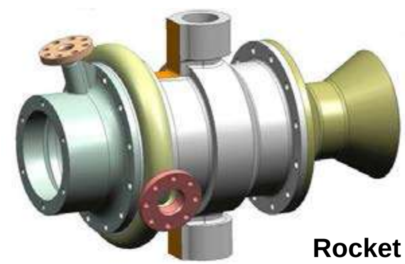
- **Basic Tool Development:**
  - Materials & Processes optimization
  - Structural design optimization for aircraft and space structures
  - Physics-based process modeling
- **Ground-Based Manufacturing:**
  - Fabrication of detailed components for engines and rockets
  - Single-piece construction of launch vehicles
  - Tailored aircraft structures
- **Space-Based Manufacturing for Supportability:**
  - Plastic (ABS) 3D printer experiment on ISS
  - Metal additive manufacturing process for ISS

NASA Ground-Based Fabrication

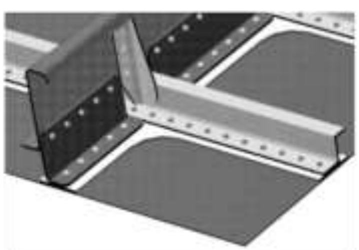
- Fabrication of components for engines and rockets
  - Rapid prototype propulsion igniter, combustion chamber and nozzle
  - GH_2/LOX engine with flight fidelity (hot-fire test demo)
  - Tailored aircraft & launch vehicle structures
    - Layered/tailored/graded stiffeners

Igniter, Combustion Chamber & Nozzle

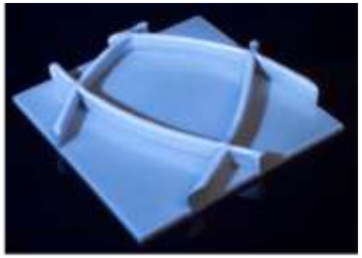
Injector



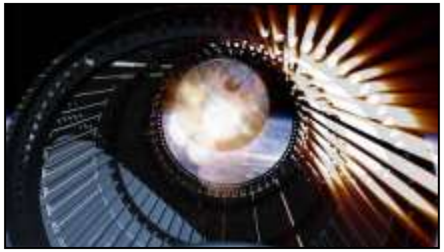
Rocket Engine



Conventional Structure



AM Structure

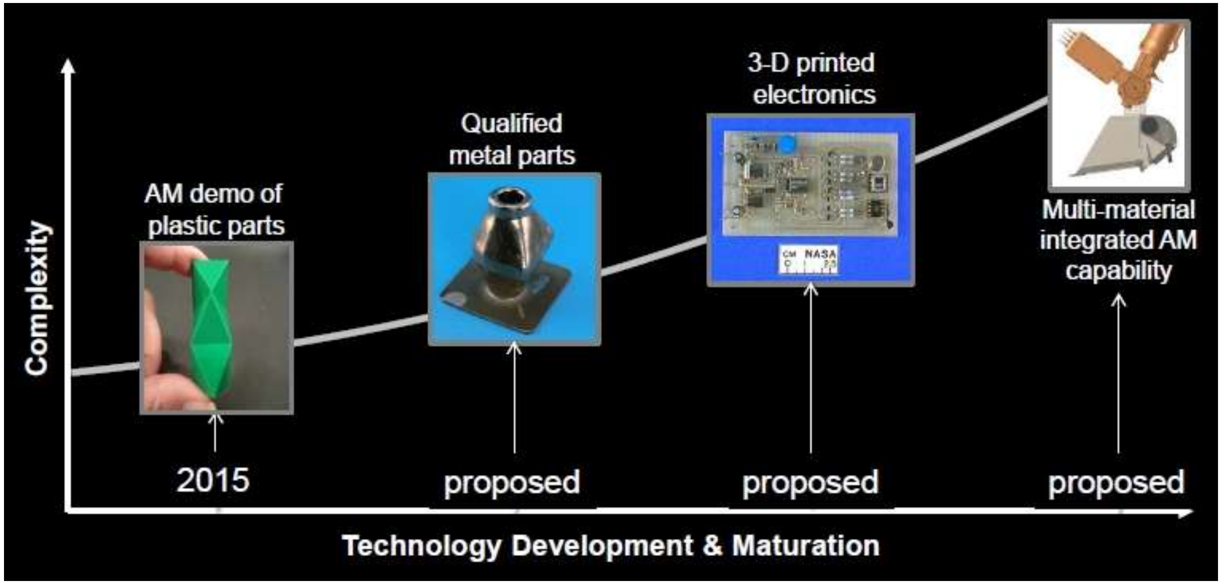


Internal stiffeners in spent fuel tank

NASA Space-Based Fabrication

- Plastic AM: Near-term 3D printer experiment on ISS
  - Made in Space, Inc. delivering 3D ABS printer to ISS for on-orbit experiment (threads, springs, caps, clamps, buckles, containers)

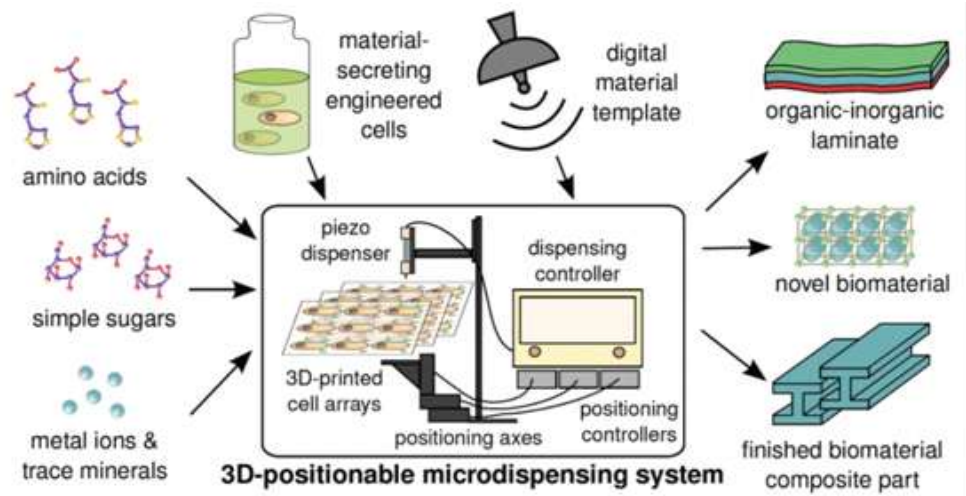
- Metal AM: Future experiment for ISS
  - Proposal being developed to deliver EBF^3 system to ISS (successful 0-g parabolic flight demo)



New Supportability Paradigm To Reduce Spares Upmass

Ames Research Center (ARC)

- Partner with MSFC for planned Fall 2014 International Space Station (ISS) Made-In-Space, Inc. 3D printing project.
- 3D printing of synthetic biology (synbio) altered cells, allowing the production of materials off planet with virtually no inputs other than in situ-sourced water, radiation, CO_2 and N_2:[§]



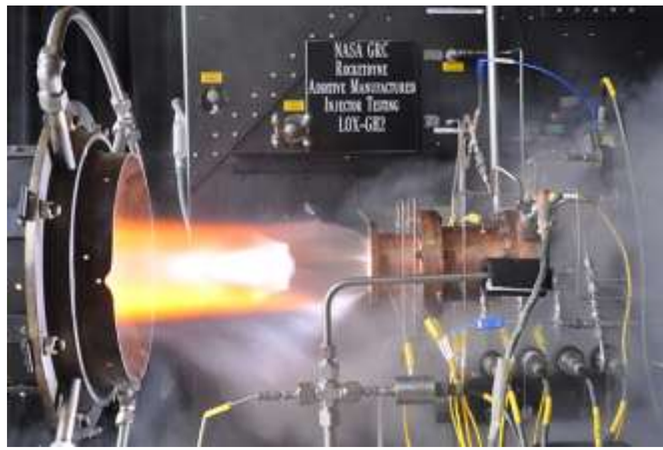
ARC's combining of synthetic biology and additive manufacturing to create 3D-structured arrays of cells that are bioengineered to secrete different materials in a specified three-dimensional pattern.

- Portable non-contact optical Surface Enhanced Raman spectrometry (SERS) to monitor the material properties during the 3D manufacturing processes.

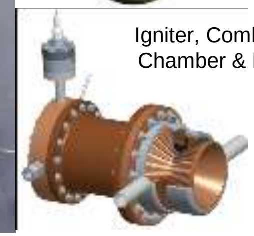
§ Gentry, D., Micks, A., and Rothschild. L., *Biomaterials out of thin air: in situ, on-demand printing of advanced biocomposites*. 2014 NIAC Symposium, Stanford University, Stanford, CA, February 4-6, 2014.

Glenn Research Center (GRC)

- Working with Aerojet Rocketdyne on an Air Force-funded project on liquid rocket gaseous hydrogen/liquid oxygen (GH_2/LOX) injectors and other structural components for a RL-10 rocket to demonstrate certification of Selective Laser Melting (SLM) and Electron Beam Melting (EBM) processes:



Injector



Igniter, Combustion Chamber & Nozzle

Hot-fire test at GRC's Rocket Combustion Laboratory of an Aerojet Rocketdyne RL-10 liquid oxygen/gaseous hydrogen rocket injector assembly built using additive manufacturing

- Working with RP+M (Avon Lake, OH) to develop polymer and ceramic technologies for a "Fully Non-Metallic Gas Turbine Engine."
- Developing methods to additively manufacture ceramics and ceramic composite materials using pre-ceramic polymers.
- In collaboration with MSFC, work is being done on:
  - Materials Genome Effort involving microstructural/phase modeling of Inconel
  - Building a GRCop-84 combustion chamber liner

Goddard Space Flight Center (GSFC)

- Production of a Ti-6Al-4V reentrant tube for a cryogenic thermal switch in the ASTRO-H Adiabatic Demagnetization Refrigerator (flight spare):

GSFC reentrant tube made by additive manufacturing for a cryogenic thermal switch for the ASTRO-H Adiabatic Demagnetization Refrigerator.

- Direct Metal Laser Sintering (DMSL) Technology Guide.
- Light-weight, low coefficient of thermal expansion optical benches for satellites and other instrument using novel Fe-Ni alloys produced by DMLS.
- Spot shielding of sensitive electronic parts to space radiation using DMLS printed Inconel 625.
- Production of proof-of-concept, fully integrated 3-D printed telescopes.
- Modulated X-ray Source being considered for a possible flight on the ISS.
- Poly(ether ketone ketone) (PEKK) battery case that flew on a sounding rocket.
- Design and build a series of CT-based Image Quality Indicators (IQIs) to assess contrast sensitivity and resolution for select space-related materials.

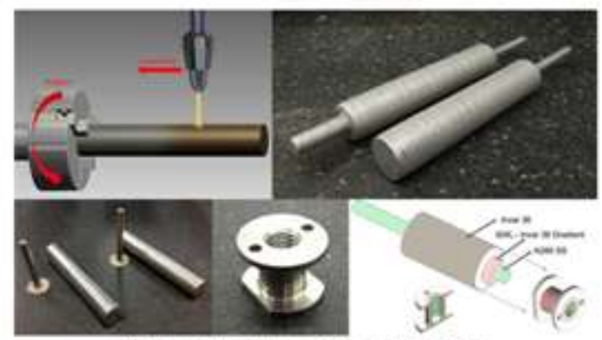
Jet Propulsion Laboratory (JPL)

- Amorphous metals, created through medial sputtering onto a surface. Specific amorphous metal projects include fabrication of a mirror assembly including the isogrid backing, and the production of a revolutionary new material for a gearbox application.
- Prototype gradient Ti-6Al-4V/niobium rocket nozzles.
- Prototype gradient stainless steel/Inconel engine valves followed by finish, prototype low CTE inserts for composites.
- Titanium mirror flexure made of deposited titanium on a titanium plate.

Laser-depositioned Titanium-Niobium rocket nozzles

Gearbox with amorphous metal gears

Amorphous Metal Mirrors



Stainless steel-Invar radial gradient alloys

A 304L-Inconel gradient alloy engine valve deposited and machine finished

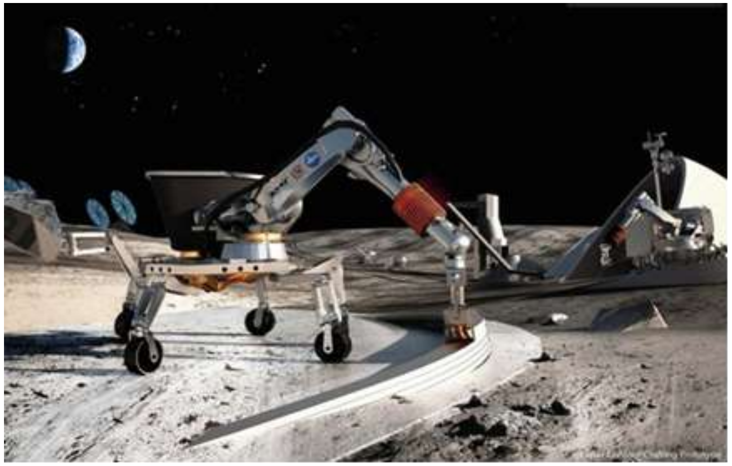
JPL metals parts made by additive manufacturing

Johnson Space Center (JSC)

- EBF3 and Laser Engineered Net-Shaping (LENS) components for manned space flight applications, including in-space manufacturing.
- Titanium, aluminum and steel EBF^3 process development and material properties test samples as well as flight-like extravehicular activity tool components, all deposited at LaRC, have been inspected in both the as-deposited and final machined conditions. NDE methods applied to the EBF3 samples and parts include X-ray digital radiologic testing (RT) and x-ray computed tomography (CT); conventional ultrasonic testing (UT) and phased array ultrasonic testing (PAUT); and eddy current testing (ECT).
- Complex conceptual engine components have been manufactured at JSC from Inconel, titanium and steel using the LENS process. Selected Inconel LENS components have been inspected using x-ray CT.

Kennedy Space Center (KSC)

- Work in the KSC Surface Systems Office and at the University of Southern California under two NIAC awards§ have shown promising results with regolith materials for in-situ heat shields, bricks, landing/launch pads, berms, roads, and other structures that could be fabricated using regolith that is sintered or mixed with a polymer binder. The technical goals and objectives are to prove the feasibility of 3D printing additive construction using planetary regolith. Future KSC effort will explore the use of NDE to show that regolith structures have structural integrity and practical applications in space exploration.



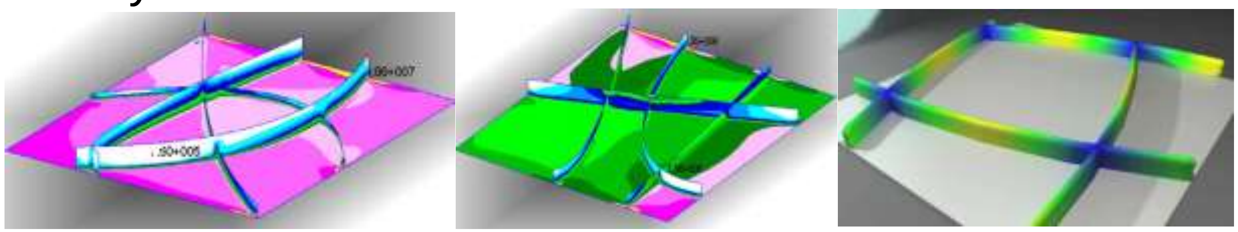
Conceptual regolith structures being fabricated on the Moon (Khoshnevis)

§ Khoshnevis, B., *Contour Crafting Simulation Plan for Lunar Settlement Infrastructure Build-Up*, University of Southern California, Los Angeles, CA 90089, NASA Innovative Advanced Concepts (NIAC) Program Phase I Award, 2011.

Khoshnevis, B., *ISRU-Based Robotic Construction Technologies for Lunar and Martian Infrastructures*, University of Southern California, Los Angeles, CA 90089, NASA Innovative Advanced Concepts (NIAC) Program Phase II Award, 2012.

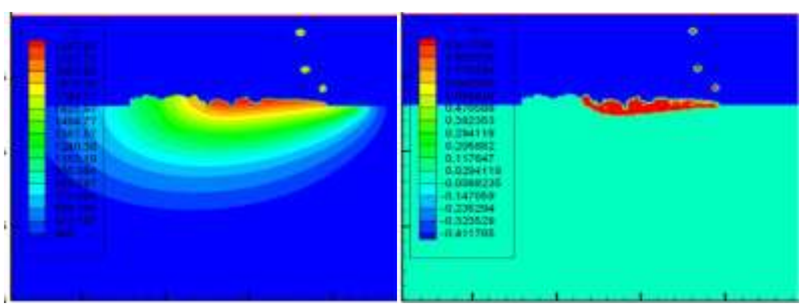
Langley Research Center (LaRC)

- Unitized structures with different alloys and integrated damage tolerance applicable including contoured stiffeners, acoustically-tailored fuselage structures, aeroelastically-tailored wing structures, functionally graded stiffeners and layered aircraft structures:

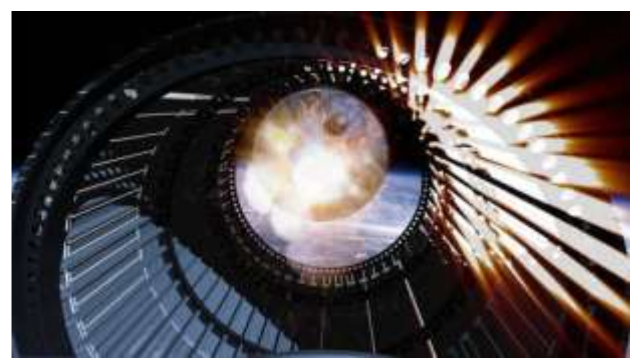


Structurally optimized panel designs (left and middle) and functionally graded panel design (right).

- Multi-scale and multi-physics modeling of laser-direct powder feed systems (LENS™, LAMP) and electron beam-wire feed systems (EBF^3).
- Integrate EBF^3 deposition of stiffeners onto single-piece cryogenic tank barrel sections of launch vehicle structures.



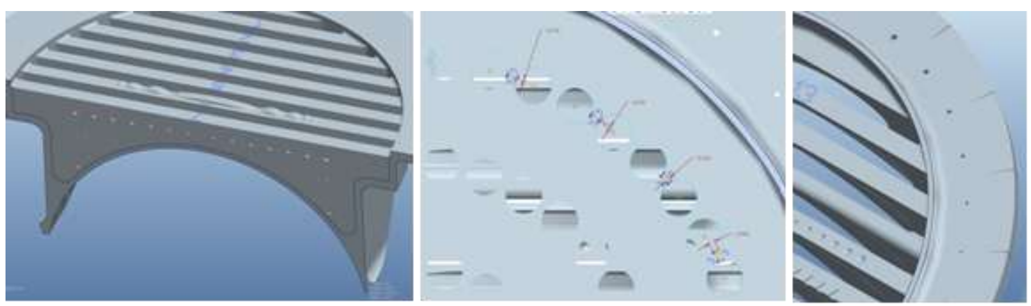
Modeling of temperature (left) and phase profile (right) during processing



Internal stiffeners in spent fuel tank

Marshall Space Flight Center (MSFC)

- Specific AM-related SLS FY14 tasks on engine components made by Direct Metal Laser Sintering (DMLS) are:
  - Characterization and testing of SLS engine components, such as turbomachinery hardware sized for the Exploration Upper Stage (EUS)
  - Hot-fire test of LOX/H_2 additively manufactured EUS integral valve/injector
  - Inconel 625 and Ti-6Al-4V material properties development
  - Additive manufacturing infrared inspection
- NDE of dozens of AM components has been conducted, primarily with CT (ET, PT, RT and UT have also been used). Some of the major components inspected are potential parts for the RS-25 and J2-X engines and Morpheus lander, including baffles, exhaust port covers, nozzles, injectors and valve bodies.
- CT analysis of gauge blocks and fabrication and testing of the POGO-Z physical reference standard:

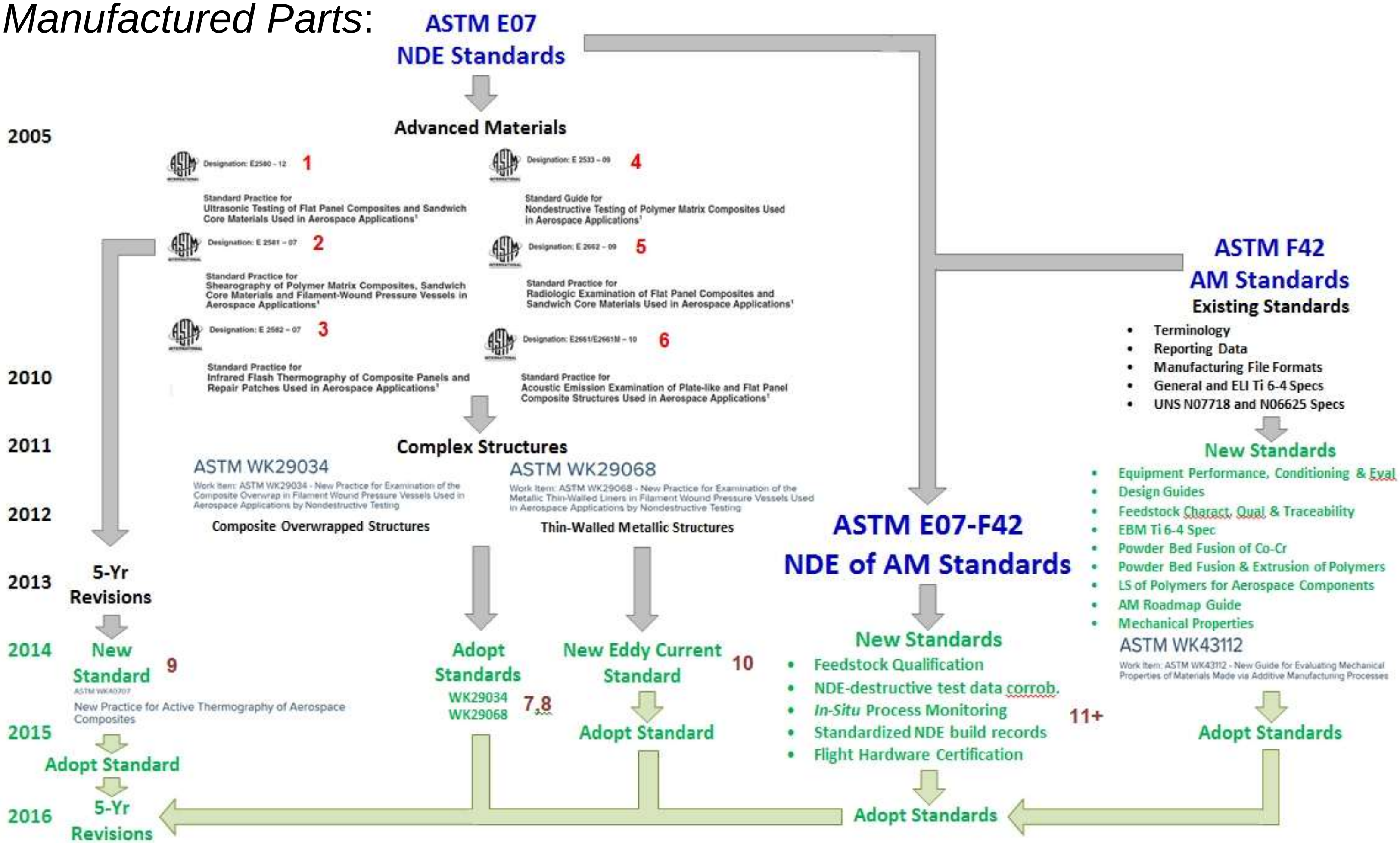


MSFC POGO-Z physical reference standard used to verify and validate NDE measurements made on additively manufactured parts.

- MSFC is working in collaboration with ARC in the planned Fall 2014 International Space Station (ISS) Made-In-Space, Inc. 3D printing project.

White Sands Test Facility (WSTF)

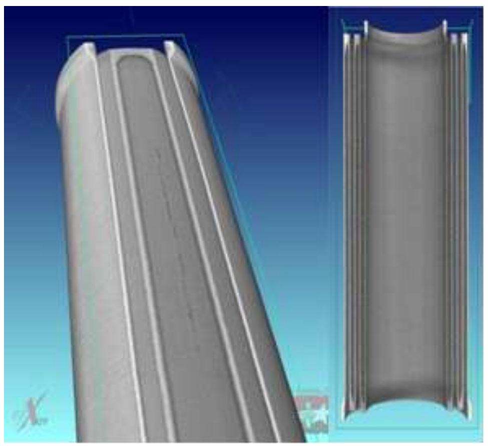
- WSTF is the liaison between American Society of Testing and Materials (ASTM) Committees E07 on Nondestructive Testing and F42 on Additive Manufacturing Technologies. The first planned standard as agreed to in June 2014 will be under the jurisdiction of E07 and be a *Guide for NDT of Additive Manufactured Parts*:



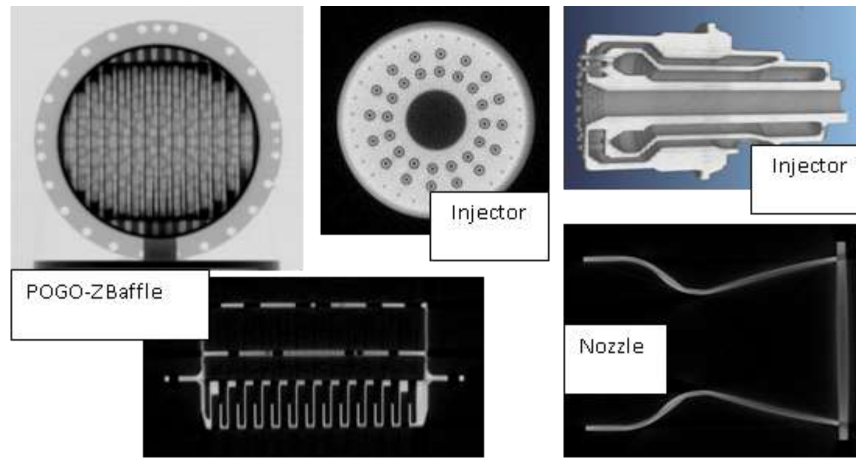
Representative NASA NDE Data on AM Parts

Representative NDE of AM Parts

- ***Computed Tomography*** – CT scans of a Ti-6Al-4V ASTRO-H adiabatic refrigerator component, RS-25 POGO-Z baffles, RS-25/J2-X nozzles, injectors and valve bodies demonstrate the ability of CT to detect simulated internal flaws and inaccessible internal features:



Computed tomography of a Ti-6Al-4V ASTRO-H adiabatic refrigerator component showing an indexing seam on an interior wall (left), and intricate internal structure (right) (GSFC).

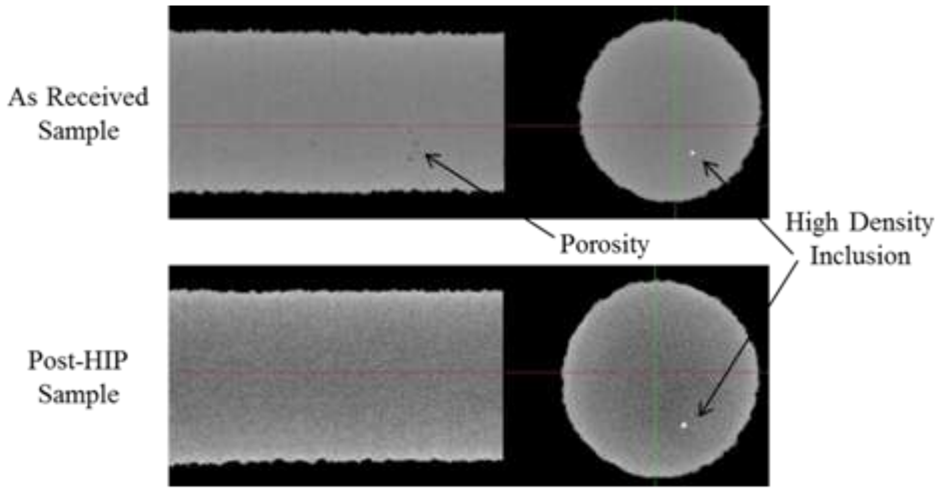


Computed tomography images of POGO-Z baffles, RS-25/J2-X nozzles, injectors and valve bodies made by a direct metal laser sintering process (MSFC).

Photography (left) and computed tomography (right) of a direct metal laser sintered POGO-Z aluminum gauge black (MSFC).

Representative NDE of AM Parts

- ***Computed Tomography*** – CT has can confirm closure of porosity by HIP post-processing, and detect high density inclusions in as-manufactured Ti-6Al-4V specimens subjected to hot isostatic pressing (HIP):



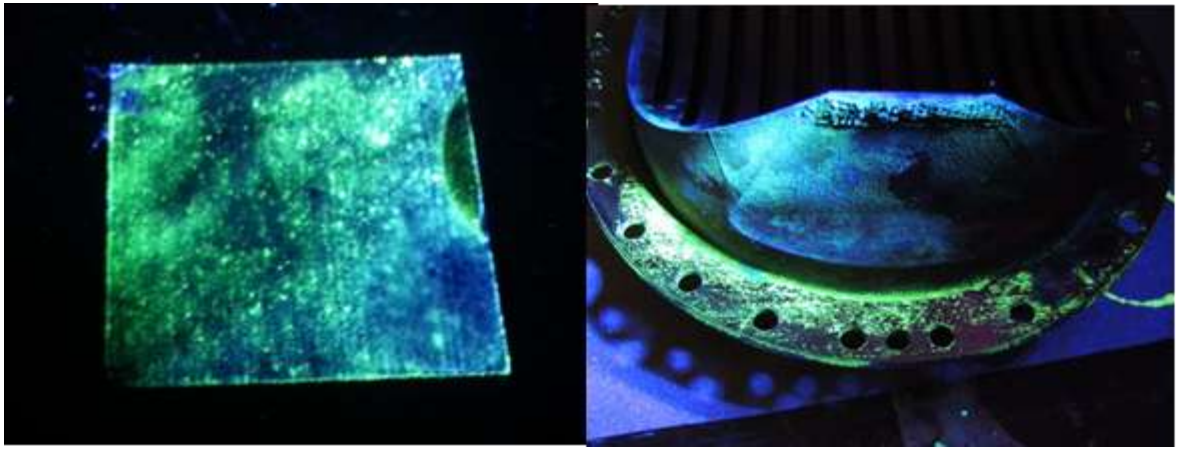
GRC computed tomography of an as-received Ti-6Al-4V tensile sample and following hot isostatic pressing (HIP) confirming closure of porosity by HIP post-processing (GRC)

This demonstrates the value of CT to 1) detect deep or embedded defects, 2) interrogate inaccessible features, 3) confirm the effectiveness of post-process treatments often required to make usable AM parts, and 4) to characterize and qualify as-manufactured AM parts.

- *Limitation of CT*: inability to reliably detect cracks since cracks oriented perpendicular to the x-ray beam.

Representative NDE of AM Parts

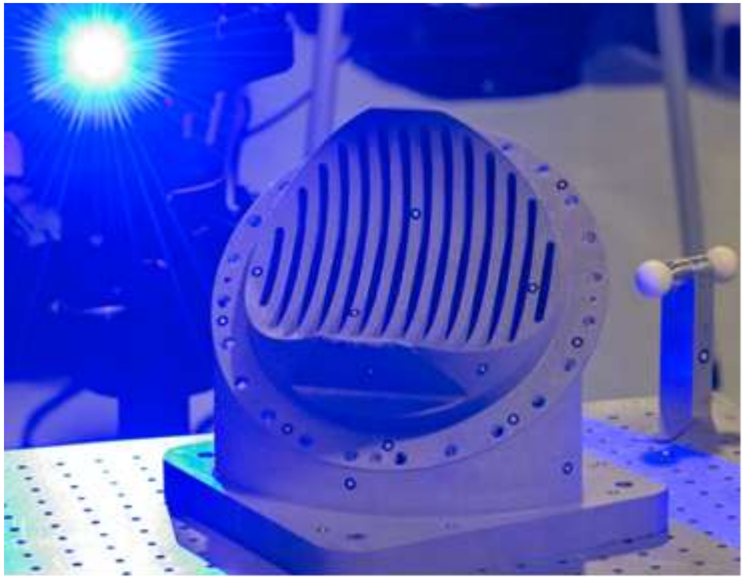
- ***Penetrant Testing*** – One of the prominent features of AM parts is higher levels of porosity compared to conventional wrought, cast or molded parts. The irregular or rough surfaces present in these parts make traditional NDE methods for the detection of surface defects difficult to impossible. For example, PT of an as-manufactured Ti-6Al-4V specimen highlights the fact that PT may not be a realistic method for inspection of porous or rough AM parts without post-process machining and polishing:



Penetrant testing of a Ti-6Al-4V block under development for a liquid rocket gaseous hydrogen/liquid oxygen (GH2/LOX) injector (left) and a POGO-Z baffle (right) showing high background noise due to as-manufactured surface roughness (courtesy of GRC and MSFC, respectively).

Representative NDE of AM Parts

- ***Structured Light*** – One of the challenges encountered in AM is maintaining dimensional accuracy of precision parts that must be made to close design tolerances. Non-contact NDE metrology methods using structured (laser/white) light can be used to monitor build accuracy *during* processing, or measure finished part dimensional accuracy and tolerances *after* processing:

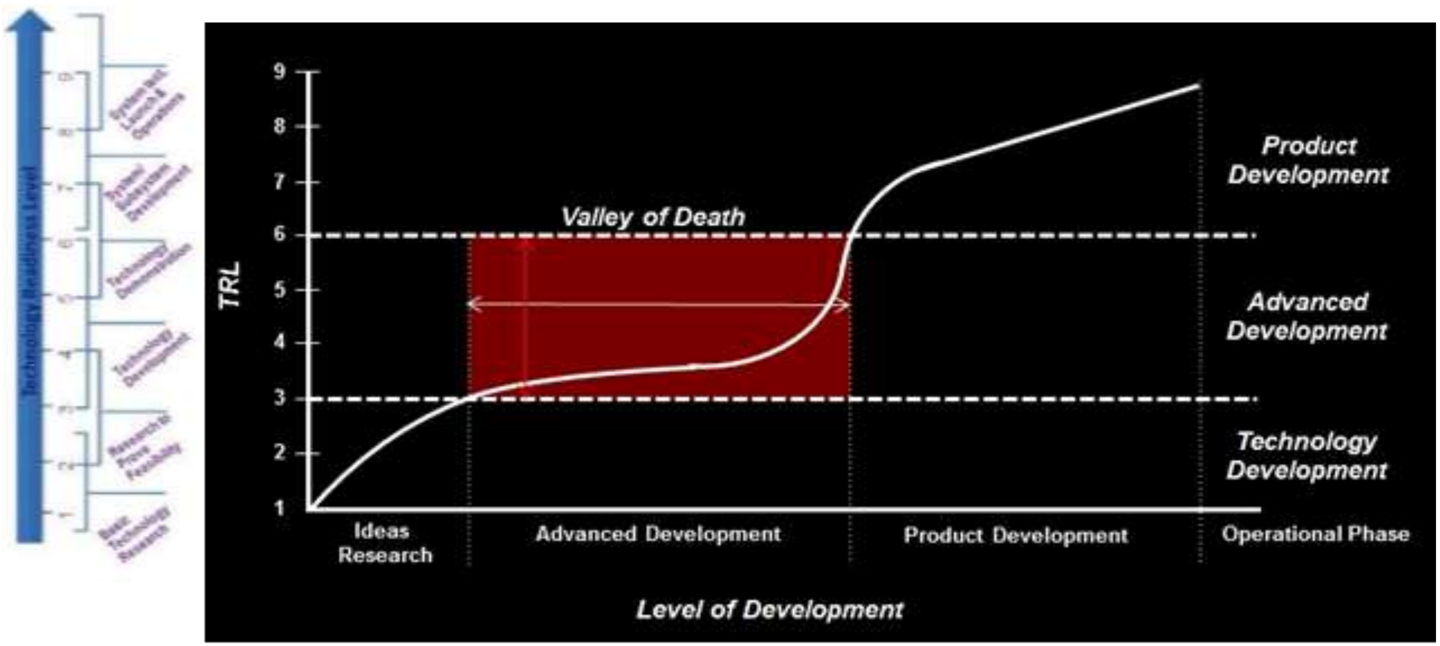


POGO-Z baffle for an RS-25 engine, built using state-of-the-art Selective Laser Melting, is inspected with a structured light scan (MSFC).

Technology Gap Analysis & Recommendations for Future NASA Effort

Technology Gap Analysis

In 2012, the National Institute of Standards and Technology (NIST) conducted a Roadmap exercise for metal AM that focused on technology gaps in measurement science.§ AM technology gaps can be conveniently grouped into five challenge areas: 1) *Materials*, 2) *Process & Equipment*, 3) *Qualification & Certification*, 4) *Standards*, and 5) *Modeling & Simulation*. Examination of these challenge areas shows that NDE is cross cutting and will play a key role in closing the gaps in each area.



Technology transition showing area of needed nondestructive evaluation development between Technology Readiness Levels 3 and 6.

§ National Institute of Standards and Technology, *Measurement Science Roadmap for Metal-Based Additive Manufacturing*, prepared by Energetics Incorporated, Columbia, Maryland, for NIST, U.S. Department of Commerce, May 2013.

Technology Gap Analysis

- Developing NDE is key challenge for Adoption of AM
- Adoption of AM parts is slow because of two issues intimately tied to NDE capability:
  - Qualification/Certification ambiguity
  - Lack of Verification/Validation processes
- Universal concern echoed throughout government, industry and academia is the path to Qualification and Verification of AM parts.
- Widespread use of additive manufacturing in NASA will require developing NDE methods that span the gap between Technology Readiness Level (TRL) 3 (analytical and experimental critical function and/or characteristic proof-of-concept) and TRL 6 (system/subsystem model or prototype demonstration in a relevant environment).

Materials Gaps

- ***Design Allowables*** – There is a lack of data on fracture toughness, fatigue strength and other key properties for AM materials. The challenge is compounded by feed stock variation. NDE can be useful in characterizing test specimens and has the potential to provide insight into the effect of defects on properties. The need for a centrally located, non-proprietary database which contains design allowables data and other pertinent information has been expressed by industry, academia and various government agencies.[§] The three aspects of the design allowables generation activity are knowledge of (1) input material, (2) process method (e.g., EB or LS), and (3) test protocol. This is a challenge or gap area where NDE can help close the gap. In other words, NDE is used a the key to elucidate *process-structure-property* relationships.
- ***Feed Stock*** – NIST has taken a lead in characterizing powder and wire feed stock materials which not only need to be consistent but also need to be optimized for AM processes. The techniques used to measure particle size, shape and chemical composition are mature.

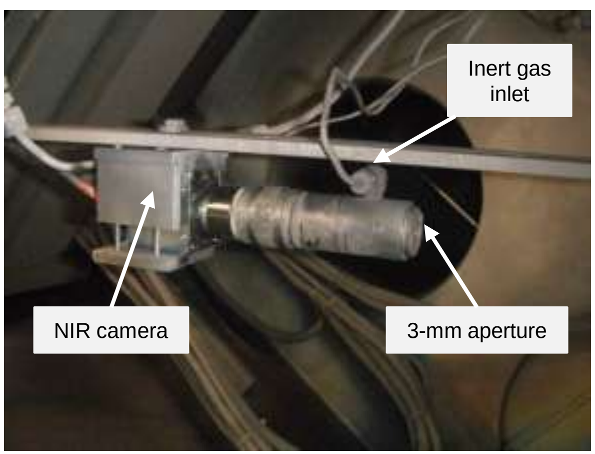
[§] Martukanitz, R., T. Simpson, and G. Messing, *The Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D)*, TTCP TP1-5 Joint Workshop, Arlington, VA, February 27, 2014, slide 13.

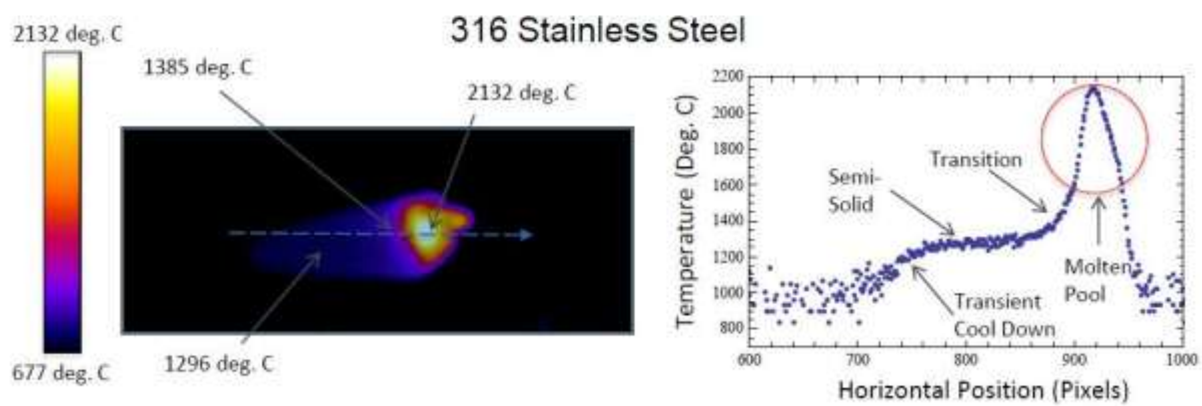
Materials Gaps (cont.)

- ***Finished Part NDE –*** Finished parts consist of both as-manufactured and post-processed parts. In both cases, NDE methods are needed to interrogate features that are unique to these parts, such as fine scale porosity, complex part geometry, and intricate or inaccessible internal features. The overall goal will be to understand the types of naturally occurring flaws produced by the AM process, what their effects are, and what NDE techniques are best suited for their detection. Specific uses of NDE to characterize AM parts may include the following:
  - Neutron diffraction to characterize the internal stress state, thus minimizing post-process warpage and distortion.
  - NDE to confirm the effectiveness of post-processing methods.
  - NDE methods to characterize gradient microstructures in parts with multiple alloys.
  - NDE methods to verify structural integrity of novel regolith and synbio materials.
  - High-resolution, high-speed, high-power CT for parts with geometrical complexity, deep porosity, or inaccessible features.
  - NDE metrology for monitor build accuracy during processing, or measuring finished part dimensional accuracy and tolerances using structured (laser/white) light.
  - Corroborate destructive test results with type, frequency and size of defects determined by NDE (effect-of-defect).
  - Corroborate fatigue properties determined by destructive test with surface characteristics (roughness, porosity/waviness) determined by NDE

Process and Equipment Gaps

- ***In-Situ Process Control –*** *In-situ* process monitoring is a requirement for producing consistent AM parts; however, current AM machines are not equipped for closed-loop feedback systems. Once it is understood what *in-situ* NDE measurements are needed, sensors deigned for the AM build environment must be developed and employed for closed-loop feedback. Thermal imaging to monitor the weld pool temperature and the thermal history of metal/plastic deposition, optical imaging to measure shape and distortion during the build, and other NDE methods for addressing residual stress, homogeneity and defects are areas for development.





EBF³ Near Infrared (NIR) camera (left) used for real time particle tracking during deposition, and temperature calibration for stainless steel (SS) 316 (right) (LaRC).

Process and Equipment Gaps (cont.)

- ***Post Processing* –** There is a need for protocols for post processes such as hot isostatic pressing (HIP), heat treating and shot peening. NDE can play role in understanding the effect of these processes on final part properties and consistency.
- ***NDE* –** The NIST report identified the need for optimizing and adapting NDE *during* and *after* processing. Thermography is a key capability for *in-situ* process monitoring. CT is a key technique for characterizing finished parts with complex geometries and the challenge of implementation of this technique is the availability of affordable high power and high resolution systems. NASA has world-class thermography and CT capabilities dispersed across the Agency. What is lacking is a knowledge base of NDE part inspections, which is needed to understand relevant defect types and detectability.
- ***In-Space Processing* –** This is a challenge area that is unique to NASA which will require the development of potentially unique equipment and processing protocols. Advances leading to closure of the many equipment and processing challenges for industrial AM manufacturing will help drive the TRL of in-space processing.

Qualification & Certification

- ***Guidelines*** – There is a recognized lack of guidelines for how to qualify & certify *both* AM processes *and* finished AM parts.
  - In the former case, qualification & certification of processes is complicated by the wide variety of machine types and the vast processing parameter space. NDE can help bridge this gap by correlating finished part properties (structure and morphology) with the process route.
  - In the latter case, qualification & certification of finished AM parts is hampered by lack of available data, poor understanding of the effect of defect, and in certain cases, inability or uncertainty in detecting the critical flaw.
- ***Need*** – Certification methods are to ensure the production and use of safe and reliable parts for spaceflight applications.
- ***Justification*** – Aligns with NASA Office of Safety and Mission Assurance goals to support human Mars missions and improve the Agency's understanding of risk contributions to spaceflight systems and the effectiveness of assurance processes.

Qualification & Certification(cont.)

- ***Approach*** – Optimized NDE methods will be combined with NDE modeling for a cost-effective methodology for verifying part quality. The approach will allow for a cost-effective approach to verifying part quality by reducing the number of standards required, particularly for limited producrtion (‘1-off’ parts) where a large number of standards are not reasonable or cost-effective.

- Certification for additive manufactured parts falls into two categories:
  - Category 1: Prototype and ‘1-off’ parts. Parts in this category consist of singular and small lot production parts. These parts will require certification but it is prohibitive to perform validation by the previous methods. “Certification for Flight” may be the outcome.
  - Category 2: Bulk production parts. Parts that fall into this category will be frequently manufactured and thus previous inspection and validation procedures can be applied to certify the part. Previous methods include establishment of probability of detection and probability of inspection.

Qualification & Certification (cont.)

Methodology for Certification of Additive Manufactured Parts

Areas of Study Required

Measurement:
Investigation into use of conventional and non-conventional Nondestructive evaluation techniques applied to various additive manufactured techniques.

Modeling:
Investigation into modeling of nondestructive evaluation techniques as applied to various additive manufacturing techniques, and establishing model-based inspection confidence.

Areas of study are mutually beneficial to each other and should be addressed concurrently to save cost. Measurement data must be used to validate models and modeling enables new capabilities (model-based inspection optimization and inspectability predictions).

Verification and Validation:
Combine use of modeling and measurement to verify that safe and reliable parts can be certified for space flight. Requires extensive testing, modeling, and application of various techniques to a variety of additive manufacturing processes.

Standards

- ***Input Material and Finished Part Standards* –** No standards exist for measuring the size, shape, chemistry or microstructural homogeneity of input materials, or the mechanical properties of finished parts. Standards for the 1) preparation of measurement test pieces, and 2) creating, reporting, and storing AM test data will be developed.
- ***Equipment Standards* –** Standards are particularly critical to ensure machine-to-machine consistency and routine or periodic calibration to ensure optimal operation and performance, and thus, part quality.
- ***Qualification and Certification Methods* –** Qualification and certification guidelines for AM processes and equipment are currently lacking or inadequate.
- ***Standards for Round-Robin Build and Material Testing* –** No standards exist for round-robin build and materials testing for AM. To address this gap, a set of protocols will be created for round-robin testing, beginning with a single source powder and going through part production, process, build, and inspection using, for example, composition (scanning electron microscope/energy dispersive spectrometry), particle size, morphology, and flowability/sifting mesh.

Standards (cont.)

- ***New Guide* –** During a meeting of ASTM Committee E07 in June 2014, it was decided to begin development of a draft *Standard Guide for Nondestructive Testing of Additive Manufactured Parts Used in Aerospace Applications*.
- The Scope of the new *Guide* will focus on mature materials (Ti-6Al-4V, Inconel alloys, certain polymers) and processes (EBM/EBF^3 and DMSL/SLM).
- The primary NDE methods considered thus far have a basis of experience and will be:
  - CT (finished metal part NDT)
  - Thermographic Testing (includes NIR cameras, *in-situ* process monitoring)
  - Structured Light (finished metal and plastic part NDT).
- ECT, PT and UT/PAUT may be incorporated at a later time pending data demonstrating beneficial 'proof-of-concept.'
- Although jurisdiction will be under E07, precedence is given to F42 standards in matters pertaining to additive manufacturing.

Standards$^{(cont.)}$

- ***New Guide for NDT of AM Parts*:**

Designation: X XXXX-XX

Work Item Number: XXXXX
Date: Sept, 30, 2014

Standard Guide for Nondestructive Testing of Additive Manufactured Parts Used in Aerospace Applications[1]

This standard is issued under the fixed designation X XXXX; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

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

1.2 The parts covered by this Guide are used in aerospace applications; therefore, the examination 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, and stainless steels. The polymers under consideration include but are not limited to acrylonitrile butadiene styrene (ABS) terpolymer and poly(ether ketone ketone (PEKK).

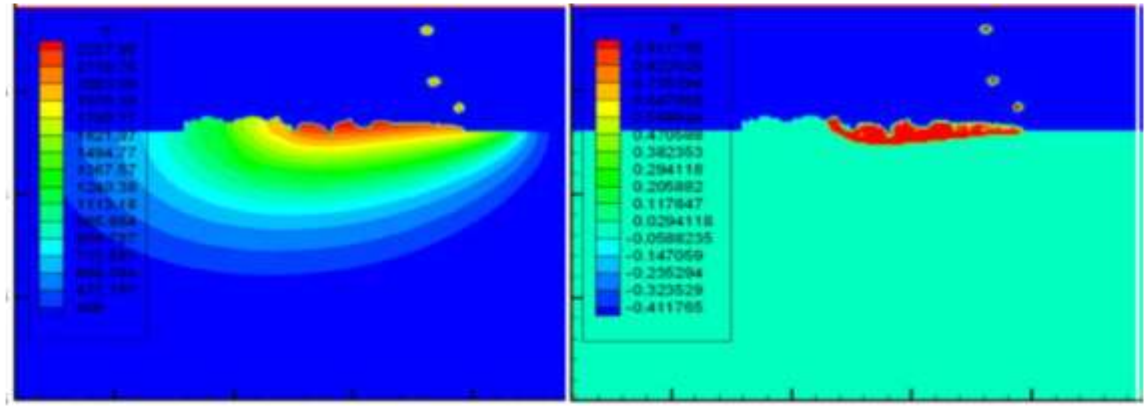
NOTE — The combustion and ignition properties of metals and polymers must be taken into account for safe use in aerospace applications.

1.4 Protocols for controlling input materials, and established processes and post-process methods are cited whenever possible. The processes considered will include Electron Beam Free Form Fabrication (EBF^3), Electron Beam Melting (EBM), Direct Metal Laser Sintering (DMSL), and Selective Laser Melting (SLM).

1.5 This Guide describes the application of established and new NDT procedures; namely, Computed Tomography (CT, Section 7), Eddy Current Testing (ECT, Section 8), Penetrant Testing (PT, Section 9), Thermographic Testing (TT, Section 10), Structured Light (SL, Section 11), and Ultrasonic Testing (UT, Section 11). These procedures address established practices that have a foundation of 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.

Modeling and Simulation

- ***Physics Based Predictive Models*** – Again due to the rapid pace of change in AM, there is a lack of physics based predictive models for the various AM processes. The models need to be able to predict residual stress, grain size distribution, spatial homogeneity, material properties and defects. NDE will play a key role in validating these models, which will be fundamental in process optimization.



Modeling of temperature (left) and phase profile (right) during processing

- ***In-Situ Sensors*** – The lack of in-situ sensor capabilities is also hindering model validation. There is a clear need to know the dynamics of weld pool temperature being achieved in a build process in order to predict the end product quality.

Recommendations - Summary

- Lack of NDE and design allowables data
  - Fabricate physical reference standards to verify and validate NDE data
  - Augment current NDE dataset to increase agency experience
  - Apply NDE to understand feedstock-process scatter in design allowables data generation activities
- Low maturity finished part NDE
  - Apply NDE to understand effect-of-defect and establish acceptance limits
  - Correlate process and destructive test data with NDE and develop process-property recommendations
- Lack of *in-situ* process monitoring
  - Implement NDE in closed-loop process control to maximize part quality and consistency, and obtain ready-for-use certified parts directly after processing
  - Develop better physics-based process models corroborated by NDE
  - Use NDE to validate and confirm the effectiveness of post-processing
- Lack of Standards for NDE of additive manufacturing
  - Develop NDE-based qualification & certification protocols for flight hardware
  - Standardize NDE build records to serve as a permanent quality record
  - NDE qualification of feedstock before build

Acknowledgements

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Michael C. Waid*, NASA Johnson Space Center, Houston, Texas*
James L. Walker*, NASA Marshall Space Flight Center, Huntsville, Alabama*

Back-up Slides

NASA NDE of AM Team Members

1/15/14 NASA Meeting Notes (host: Walker)

Attended => **Walker, Russell, Roth, Saulsberry, Stanley, Martin, Waid, Waller, Koshti, Madaras, Burke (other participants not mentioned: Parker, Hodges, Taminger, etc.)**

Went around and each Center discussed AM proposal plans:

- GRC => Focusing on Titanium; CT/Materials characterization study; CT/UT/PT of small mechanical test samples; CT/PT trials on a gimbal component; State-of-the-Technology report (collab. with WSTF)
- JSC => Focusing on Titanium; Making samples with varying quality and comparing to wrought baseline; CT/ET/PT/UT
- LaRC => Make e-beam samples; Modelling for UT of AM parts; Discussed using AM to make controlled defects for NDE standards; Brought up the issue of POD and how it would be done for AM parts
- MSFC => Defect formation (Laser sintered Inconel AM); effects-of-defects; NDE of defects; Industry survey for NDE for AM using a POGO-Z baffle as a test case
- WSTF => State-of-the-Technology report (collab. with GSFC); ASTM E07/F42 NDE of AM standards

Discussed need to start formulating a team to bring all the data together to help give AM NDE some focus.

NDE of NASA AM Parts & Components

- GRC: NDE is being used in the testing of material characterization samples and the development of test plans for full scale components (e.g., Inconel® 625 injectors). Specifically, computed tomography (CT) is being performed on all samples and ultrasonic testing (UT) and penetrant testing (PT) are being used on machined surfaces.
- MSFC: Past work includes an Advanced Development Office (ADO)-funded task titled "Characterization of Direct Metal Laser Sintering (DMLS) Materials for SLS Engine Components", to investigate applications of NDE to additive manufacturing materials, methods for defect standard formation, and effects of defects on material properties. Inspection of dozens of AM components has been conducted, primarily with CT, but also with ET, PT, RT and UT, to help verify their integrity and to evaluate the usefulness of these methods on "real" components.

Status: State-of-Technology Report on Additive Manufacturing

(Hughitt) Traditional quality assurance processes apply to NASA AM effort:

- qualification of equipment
- qualification of production process/products (first article inspection)
- periodic inspection of equipment
- verification of raw materials
- workmanship requirements
- in-process inspection/NDE
- production and calibration standards
- materials testing
- process and variation control

Individualized process/product-specific inspections, including NDE, need to be developed to satisfy the above general QA categories.

- Need to cap off manufacturing versus end-user (NASA) NDE

Outline of “State-of-Discipline” report will roughly follow the above, and will directly reflect technological “pull.”

Application of NDE: Life Cycle Considerations

In terms of a future action plan, NDE will first be applied to ground-based manufacturing and end user environments, prior to application to space-based environments.

In other words, while the ultimate goal may be to apply mature (high TRL) NDE methods to AM parts used in space environments (during in-space manufacturing and structural health monitoring of AM hardware), NDE methods will first be matured and applied to AM parts at the manufacturer (during in-situ process control and post-process inspections), and the end user (during receiving inspections of finished parts, qualification and certification of flight hardware, and periodic remove and inspect requalification).

America Makes/NAMII

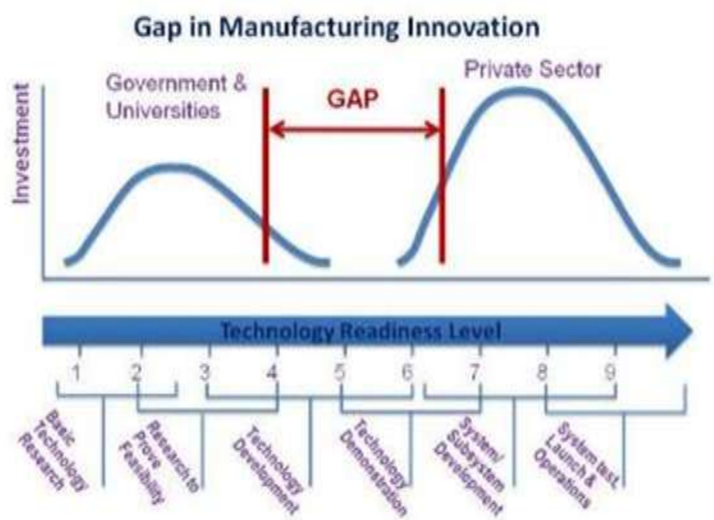
- **America Makes was formerly the NAMII (National Additive Manufacturing Innovation Institute)**
  - Leader in collaborative partnerships in additive manufacturing and 3D printing technology research
  - America Makes working to fast-track AM and 3DP technologies to increase US global manufacturing competitiveness

America Makes is a Manufacturing S&T team-led, multi-agency collaboration between industry, government and universities

- **America Makes is structured as a public-private partnership**
  - Member organizations (88 total) from industry, academia, government, non-government agencies, and workforce and economic development resources.
  - Develop long-term investment strategies and road mapping in support advanced R&D activities through crowd-funded projects.
  - Shared equipment and facilities open to industry (new center in Youngstown, OH)
  - Educational outreach and worker training resources

America Makes/NAMII

- **Current national focus is to enable technology transfer and commercialization**
- **Addresses Technology Readiness Level (TRL) 4-7**
  - Bridge gap in between R&D and Manufacturing Implementation



- **NAMII has sponsored two Project Calls since their 2013 inception**
  - **Project Call #1 for TRL 4-5 technologies**
    - 6 projects, \$9.5M, 35 partners
  - **Project Call #2 for TRL 9-10 technologies**
    - 15 projects, \$19M, 75 partners
    - Design, Materials, Processes & Equipment, Qualification & Certification, Knowledgebase development

- Thermal imaging process monitoring
- Laser sintered space vehicle components
- Modeling of ULTEM™ aerospace parts

UT inspection of Ti parts

America Makes Member Organizations

3D Systems Corporation*
3M
Alcoa
Allegheny Technologies Incorporated*
Applied Systems and Technology Transfer (AST2)*
Arkema, Inc.
ASM International
Association of Manufacturing Technology*
Bayer Material Science*
The Boeing Company
Carnegie Mellon University*
Case Western Reserve University*
Catalyst Connection*
Concurrent Technologies Corporation*
Deformation Control Technology, Inc.
DSM Functional Materials
Energy Industries of Ohio*
EWI
The ExOne Company*
General Electric Company (GE)*
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Illinois Tool Works, Inc.
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RP+M
RTI International Metals, Inc. *
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SME*
Solid Concepts
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University of Texas at El Paso
University of Toledo
USA Science and Engineering Festival
Venture Plastics, Inc.
Westmoreland County Community College*
West Virginia University
Wohlers Associates, Inc.*
Wright State University
Youngstown Business Incubator*
Youngstown State University*
Zimmer, Inc.

*Lead Members listed in **RED($200K)***
*Full Members listed in **BLUE ($50K)***
*Supporting Members in **BLACK ($15K)***
** Original Members (39)*

America Makes
National Additive Manufacturing Innovation Institute

Overview of TTCP

http://www.acq.osd.mil/ttcp/

The Technical Cooperation Program (TTCP) is an international organization that collaborates in defense scientific and technical information exchange; program harmonization and alignment; and shared research activities for the five nations.

Additive Manufacturing Standardization Needs

Traditional quality assurance processes would apply to AM:

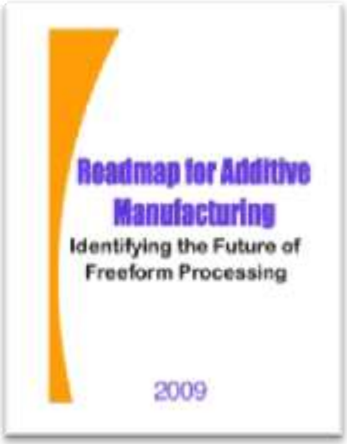
- qualification of equipment
- qualification of production process/products (first article inspection)
- periodic inspection of equipment
- verification of raw materials
- workmanship requirements
- in-process inspection/NDE
- production and calibration standards
- materials testing
- process and variation control

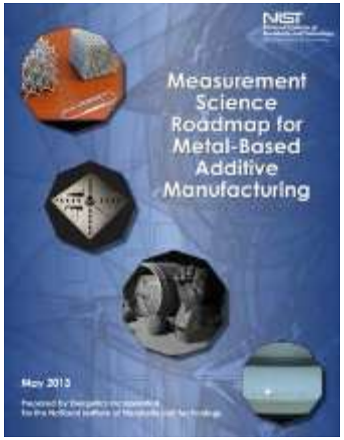
However, individualized process/product-specific inspections, NDE, etc. to satisfy these general QA categories would also need to be developed, and little if anything is being done in this regard for NASA flight hardware.

NIST Standardization and NDE Efforts

National Institute for Standards & Technology

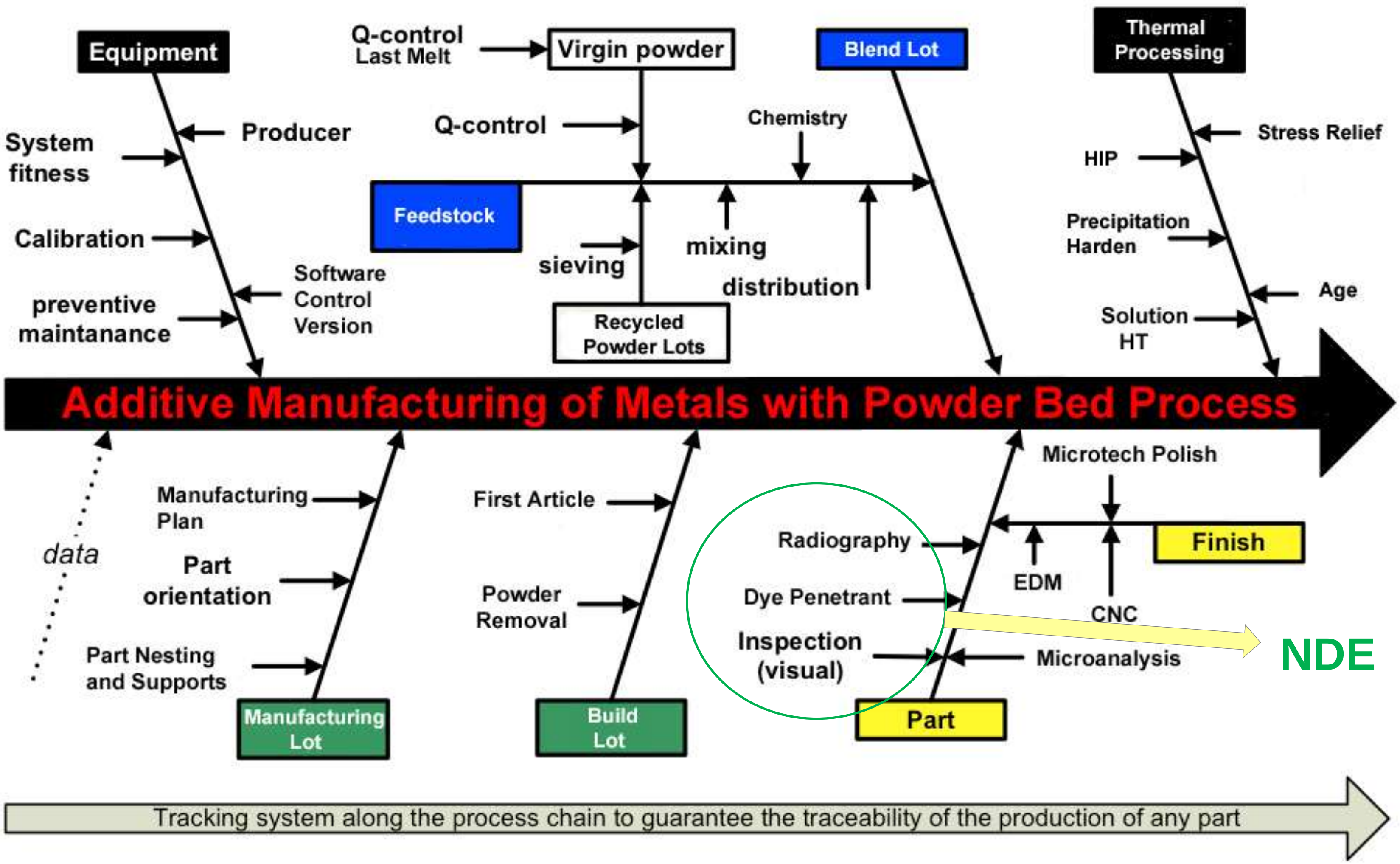
- Has developed/participated in Roadmaps for AM
- Is developing AM standards with ASTM F42 Committee on Additive Manufacturing Technologies
  - Data formats
  - Input materials control
  - Process control (includes *in-situ* NDE monitoring)
  - Finished part qualification & certification
  - However, no NDE of AM Parts standards *yet* (ASTM E07-F42 collaboration initiated in January)
  - NDE development areas
    - Neutron imagining to assess thermal stresses, collaboration with ORNL
    - Ultrasonic Porosity Sensor: Process Monitoring
    - z-Axis Interferometer Measurements





http://events.energetics.com/NIST-AdditiveMfgWorkshop/pdfs/NISTAdd_Mfg_Report_FINAL.pdf
http://wohlersassociates.com/roadmap2009.pdf

Use of NDE to Improve AM Part Consistency



Courtesy of S. Collins, Oxford Performance Materials, Inc.

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Committee F42 on Additive Manufacturing Technologies

Staff Manager: Pat Picariello 610-832-9720

ASTM Committee F42 on Additive Manufacturing Technologies was formed in 2009. F42 meets twice a year, usually in January and July, with about 70 members attending two days of technical meetings. The Committee, with a current membership of approximately 100, has 3 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.

See all ASTM Intl. videos at YouTube

Recommended

General Information

- F42 Scope
- Committee Officers and Staff Support

Get Involved

- Membership Information and Application
- New Member Orientation

Active ASTM F42 Standards

There 5 active F42 standards in the following areas:

Test Methods

ISO/ASTM52921-13 Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies

Design

ISO / ASTM52915 - 13 Standard Specification for Additive Manufacturing File Format (AMF) Version 1.1

Materials and Processes

F2924-12a Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion

F3001-13 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion

Terminology

F2792-12a Standard Terminology for Additive Manufacturing Technologies'

ASTM F42 Work Items

And 21 work items (standards under development):

Test Methods

WK30107 New Practice for Reporting Results of Testing of Specimens Prepared by Additive Manufacturing

WK40419 New Test Methods for Performance evaluation of additive manufacturing systems through measurement of a manufactured test piece

WK43112 New Guide for Evaluating Mechanical Properties of Materials Made via Additive Manufacturing Processes

Design

WK26367 New Terminology for Lattice Structures

WK37892 New Guide for General Design using Additive Manufacturing

WK38342 New Guide for Design for additive manufacturing

Materials and Processes

WK28741 New Specification for Electron Beam Melting (EBM) Titanium 6Al-4 V ELI

WK26106 New Specification for Material Qualification for Additive Processes

WK26105 New Specification for Material Traceability for Additive Processes

WK26102 New Specification for Metrics for Initial Conditioning of Machines &/or Performance Metrics for Metal Deposition

WK25296 New Specification for Electron Beam Melting (EBM) Titanium 6Al-4V

WK25479 New Guide for Conditioning of machines and performance metrics of metal laser sintering systems.

WK27752 New Specification for Powder Bed Fusion of Plastic Materials

WK30557 New Specification for Standard Specification for Laser Sintering High Melt Temperature Polymers for Non-Structural Aerospace Components

WK33776 New Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion

WK33833 New Specification for Additive Manufacturing Cobalt-28 Chromium-6 Molybdenum with Powder Bed Fusion

WK37654 New Practice for Machine Operation for Directed Energy Deposition of Metals

WK37658 New Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion

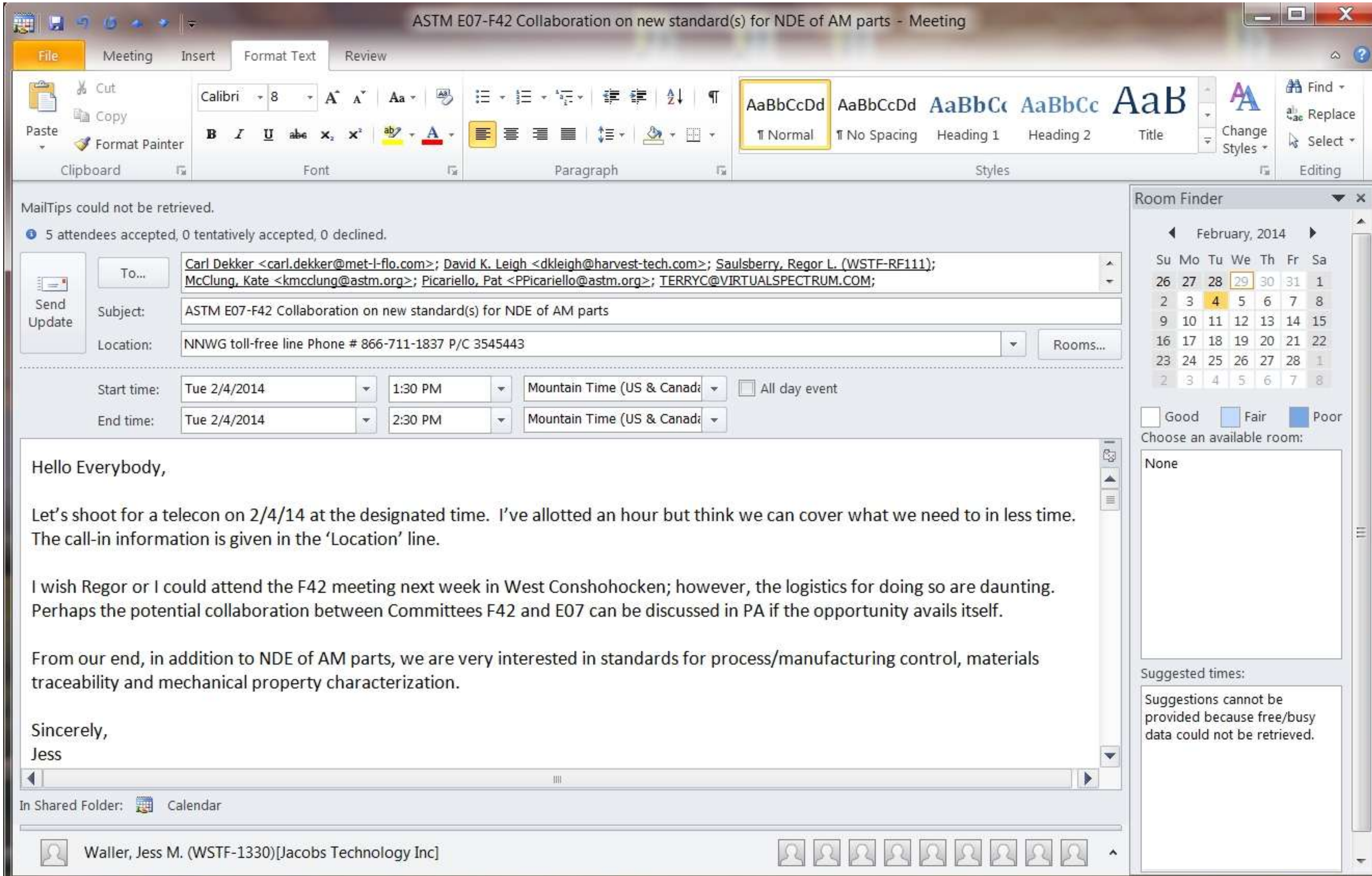
WK40606 New Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing

WK40638 New Guide for The Roadmap of F42.05 Materials and Process Subcommittee on Additive Manufacturing

Terminology

WK26433 New Terminology for Directed Energy Deposition Additive Manufacturing Technologies

ASTM Committee E07-F24 Collaboration



NDE of Flat Panel Composite Standards

Designation: E2580 – 12

Standard Practice for
Ultrasonic Testing of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications[1]

Designation: E 2581 – 07

Standard Practice for
Shearography of Polymer Matrix Composites, Sandwich Core Materials and Filament-Wound Pressure Vessels in Aerospace Applications[1]

Designation: E 2582 – 07

Standard Practice for
Infrared Flash Thermography of Composite Panels and Repair Patches Used in Aerospace Applications[1]

NDE of Flat Panel Composite Standards

Designation: E 2662 – 09

Standard Practice for
Radiologic Examination of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications[1]

Designation: E 2533 – 09

Standard Guide for
Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications[1]

Designation: E2661/E2661M – 10

Standard Practice for
Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Applications[1]

ASTM WK29034

Work Item: ASTM WK29034 - New Practice for Examination of the Composite Overwrap in Filament Wound Pressure Vessels Used in Aerospace Applications by Nondestructive Testing

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

ASTM WK29068

Work Item: ASTM WK29068 - New Practice for Examination of the Metallic Thin-Walled Liners in Filament Wound Pressure Vessels Used in Aerospace Applications by Nondestructive Testing

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