



Additive Manufacturing for Space Applications

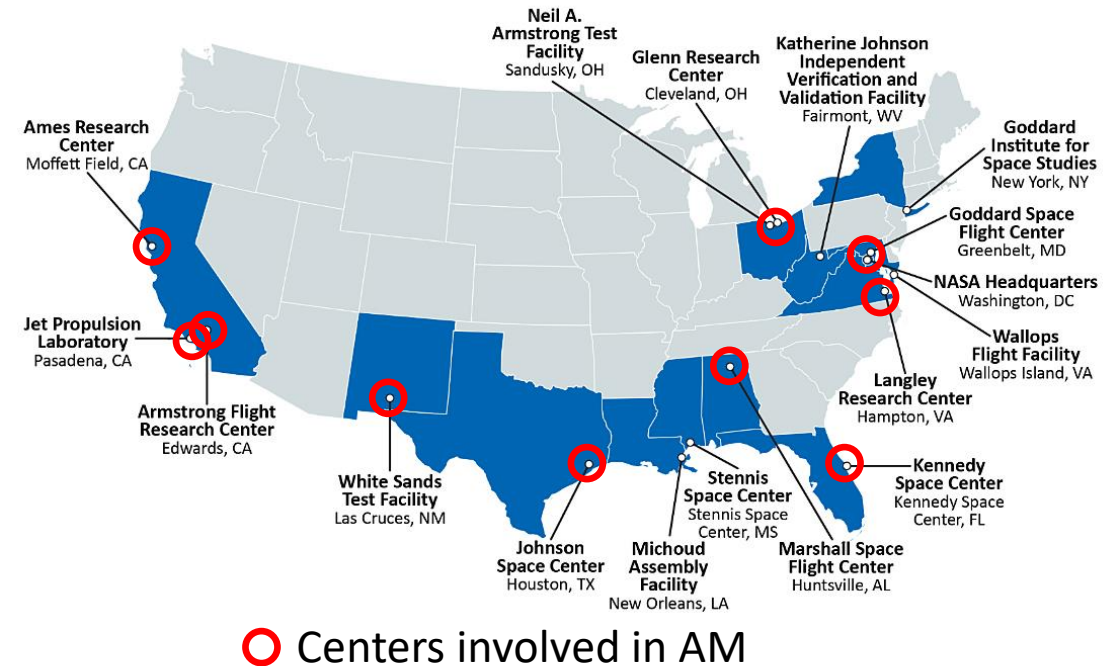
Rick Russell, NASA Technical Fellow for Materials

Aircraft Airworthiness and Sustainment Conference
Jacksonville, FL
August 31, 2022



Additive Manufacturing at NASA

- Fully embraces advantages of AM
 - Cost/lead time/part count reduction, new design and performance opportunities, rapid design-fail-fix cycles
- While fully understanding the challenges
 - Especially in delivering high value, high performance AM hardware
- NASA has dual roles
 - Drive and foster AM technology research and development in support of broad industry adoption and industrialization
 - Develop protocols for spaceflight hardware certification for access to space that can safely meet mission objectives





Additive Manufacturing at NASA

AM Technology Maturation

- AM Processes, Alloy, Part Development
- AM Process Selection – criteria, comparison, integrated evaluation
- New AM-able alloy development
- AIAA Book
- Material database metal AM properties to aid conceptual designs
- STRI Proposal call
- Tipping Point/ACOs/Commercial Partnerships
- Out of the world AM

Spaceflight AM Hardware Certification and Qualification

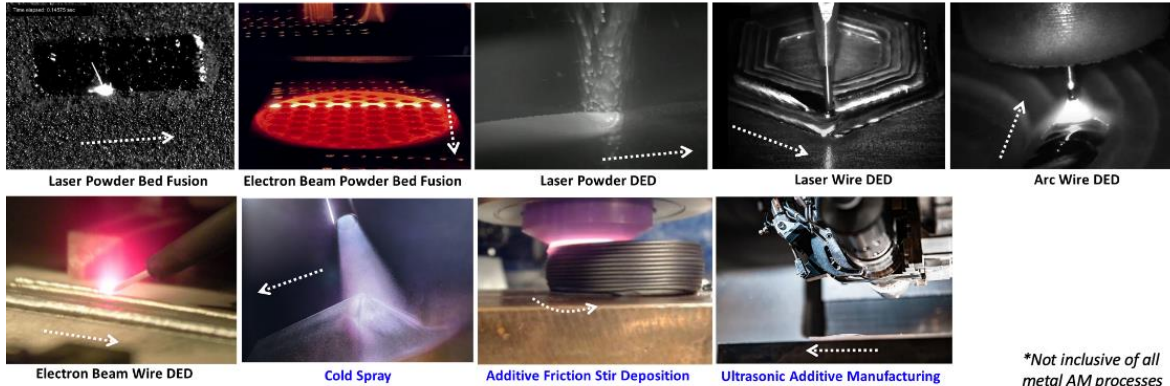
- NASA-STD-6030 and 6033
- Agency-wide AACT Team– AM Cert competency development + associated projects
- Active flight program insight activities
- Role of NDE and In Situ Process Monitoring
- Computational models for AM process validation
- Fracture control of un-inspectable AM parts



AM Technology Maturation and Process Selection



AM Processes for various applications

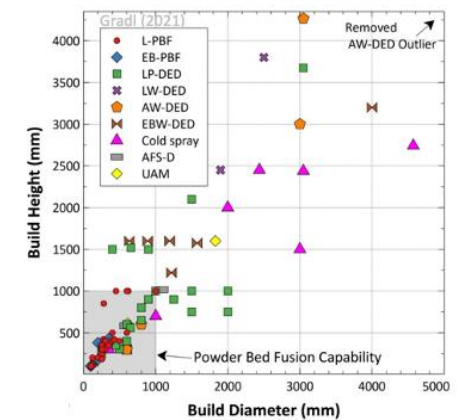
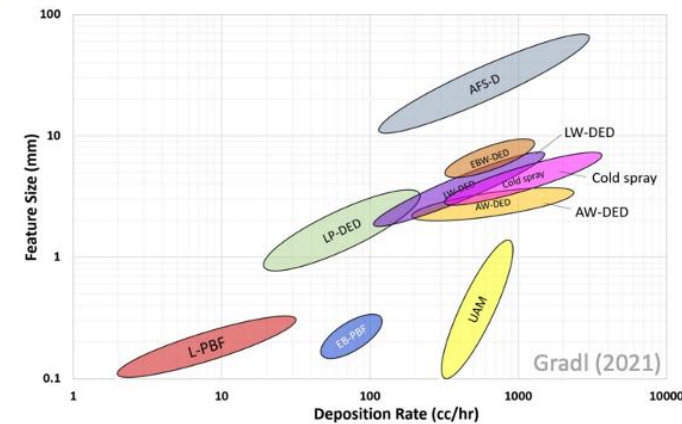


*Not inclusive of all metal AM processes

A) Laser Powder Bed Fusion [https://doi.org/10.1016/j.actamat.2017.09.051], B) Electron Beam Powder Bed Fusion [Credit: Courtesy of *Freemelt AB*, Sweden], C) Laser Powder DED [Credit: *Formalloy*], D) Laser Wire DED [Credit: *Ramlab* and *Cavitar*], E) Arc Wire DED [Credit: *Institut Maupertuis* and *Cavitar*], F) Electron Beam DED [NASA], G) Cold spray [Credit: *LLNL*], H) Additive Friction Stir Deposition [NASA], I) Ultrasonic AM [Credit: *Fabrisonic*].

Gradi, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., McKinney, C. (2021). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". (Journal Article In Release)

Various criteria for selecting AM techniques



Complexity of Features

Scale of Hardware

Material Physics

Cost

Material Efficiency

Speed of Process

Material Properties

Internal Geometry

Availability

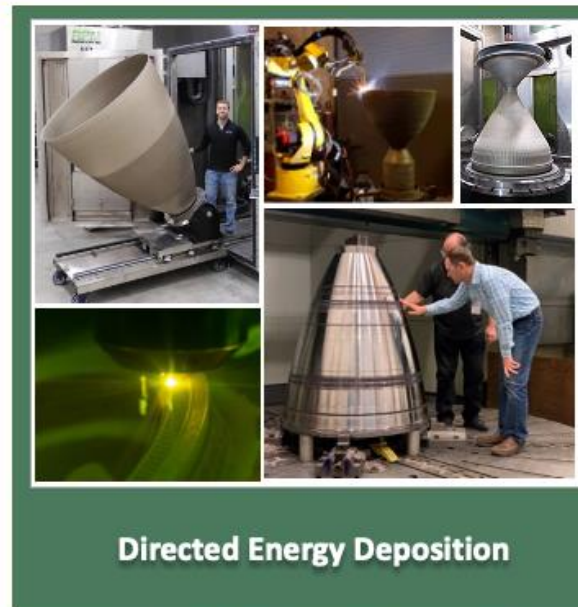
Post Processing



AM Technology Maturation

Rocket Engine Part Development and Hot Fire Testing

Additive Manufacturing (AM) Development at NASA for Liquid Rocket Engines





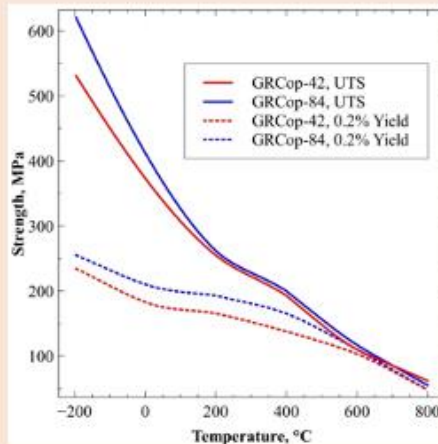
AM Technology Maturation - New Alloy Development



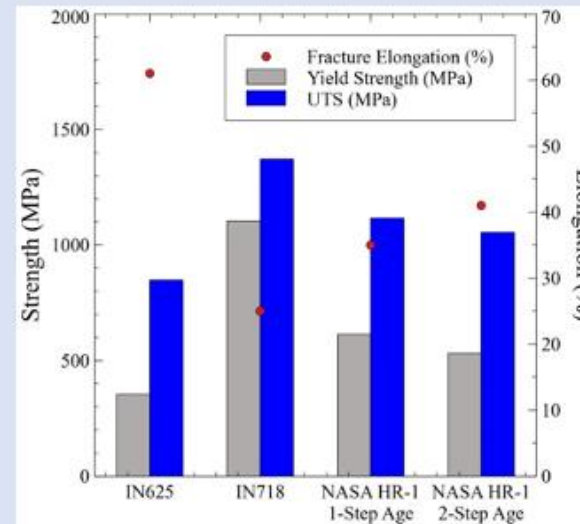
Enabling New Alloy Development using Additive Manufacturing



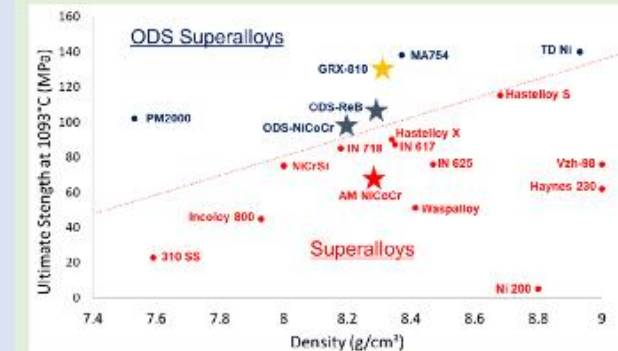
GRCo-42, High conductivity and strength for high heat flux applications



NASA HR-1, high strength superalloy for hydrogen environments



GRX-810, high strength, low creep rupture and oxidation at extreme temperatures



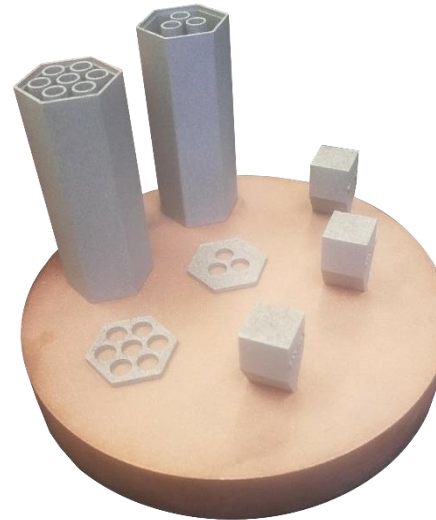
Ref: Tim Smith, Christopher Kantzos / NASA GRC 12



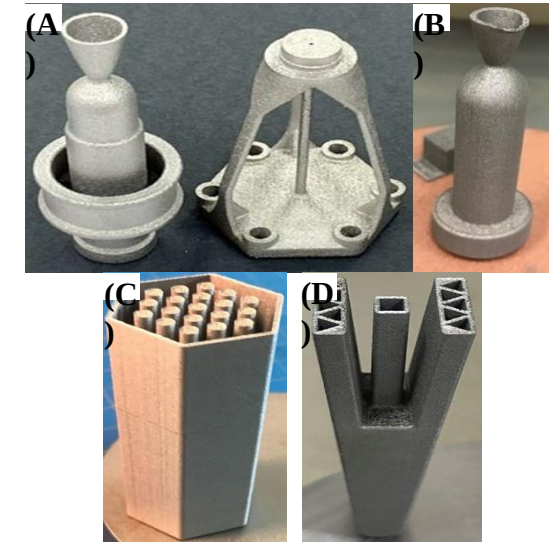
AM Technology Maturation - Refractory Alloy Development



- Refractory manufacture at MSFC
 - NTP fuel development (FY11-present)
- Refractory AM demonstrated using:
 - Laser powder bed fusion (L-PBF)
 - Electron beam PBF (EB-PBF)
 - Laser powder DED (LP-DED)
 - Electron beam wire DED (EW-DED)



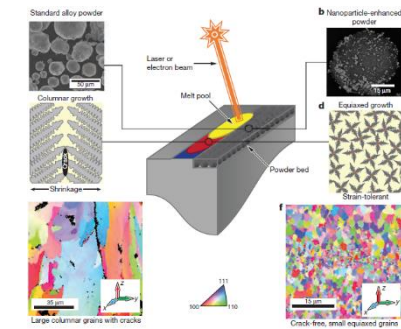
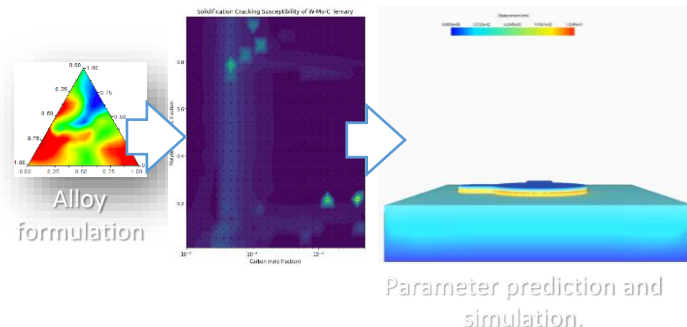
First NASA W AM build: NTP fuel clad with integrated coolant channels.



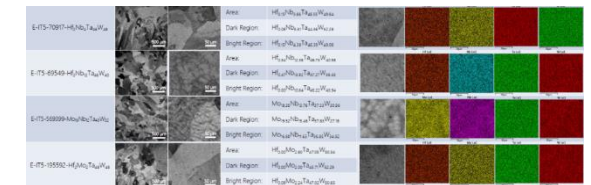
L-PBF AM (A) C103 1 N reaction chamber and thrust stand-off, (B) 1N AM W chamber, (C) AM W NTP fuel clad, (D) AM W hypersonic wing leading edge with integrated heat pipe channels.

• Design AM-optimized refractory alloys

- Integrated Computational Materials Engineering (ICME).
- Melt/solidification transformation and dynamics, crack susceptibility, AM build simulation, and property prediction.
- NASA Ames Research Center & NASA MSFC lead.



Nano-powder dispersoid stabilization and strengthening [1].



RHEA specimen characterization. Courtesy TAMU.



AM Technology Maturation – Writing a book!



Metal Additive Manufacturing for Propulsion Applications

Edited by
Paul R. Gradl, Omar R. Mireles,
Christopher S. Protz, and Chance P. Garcia



PROGRESS IN ASTRONAUTICS AND AERONAUTICS

Timothy C. Liewen, Editor-in-Chief
Volume 263

<https://arc.aiaa.org/doi/book/10.2514/4.106279>

Online version available now and hardcopy in mid-August

P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022). *Metal Additive Manufacturing for Propulsion Applications*. AIAA Progress in Astronautics and Aeronautics Book Series.

<https://arc.aiaa.org/doi/book/10.2514/4.106279>

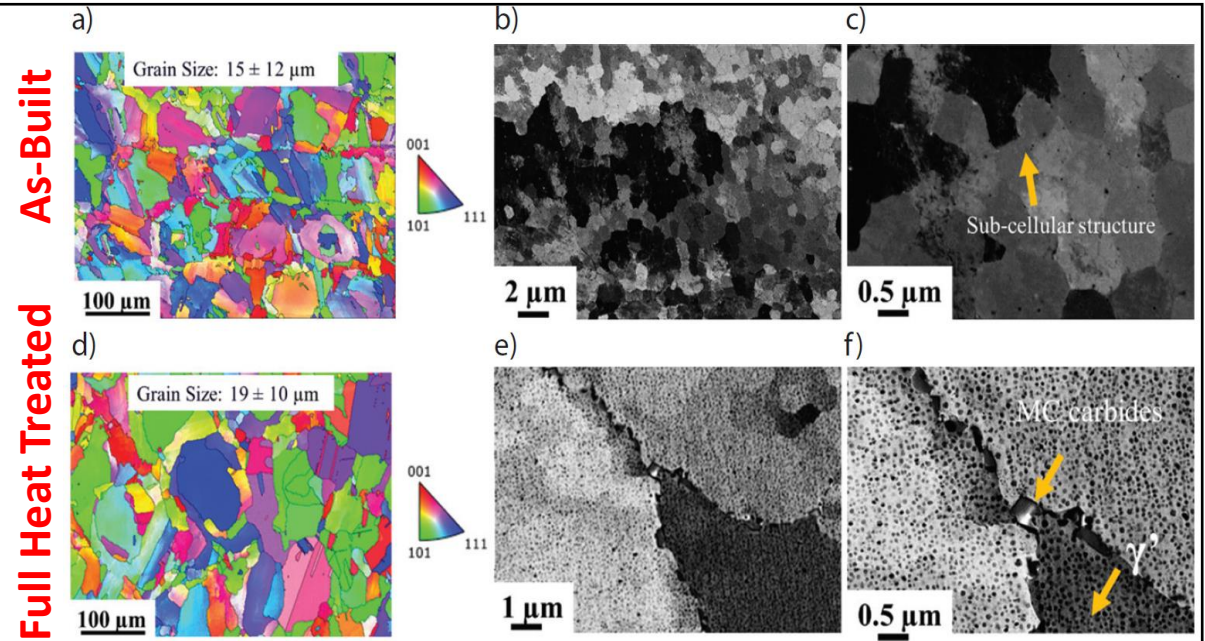
Additive manufacturing (AM) processes are proving to be a disruptive technology and are grabbing the attention of the propulsion industry. AM-related advancements in new industries, supply chains, design opportunities, and novel materials are increasing at a rapid pace. The goal of this text is to provide an overview of the practical concept-to-utilization lifecycle in AM for propulsion applications.



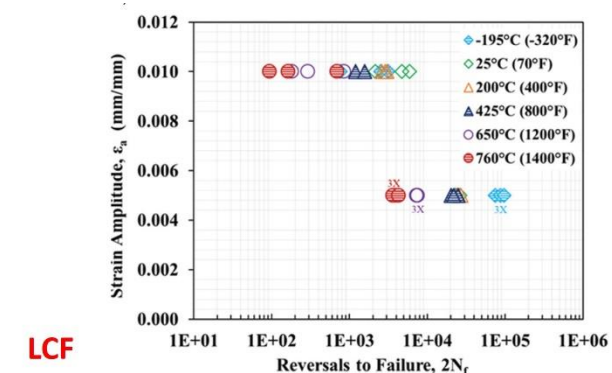
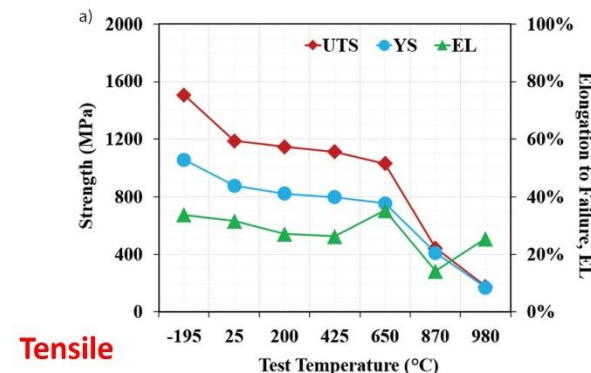
AM Technology Maturation – Property Database

Material	Power (W)	Layer Height (mm)	Scan Speed (mm/s)	Hatch Distance (mm)
Haynes 282	285	0.04	960	0.13

Procedure (Designation)	Temperature (°C)	Time (hrs)	Cooling
Stress Relief (SR)	1065	1.5	Furnace cool
HIP [2]	1162/103 MPa	3.5	Furnace cool
Solution Annealed (SOL)	1135	1	Argon quench
Double Step Aging (AGE)	1010	2	Furnace cool at 10°C/min
	788	8	2 bar Argon gas at 20°C/min

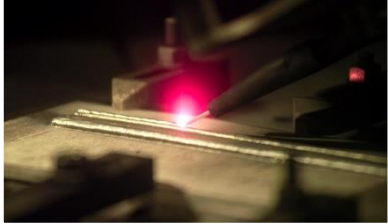


- Obtained material samples from L-PBF and LP-DED vendors with full traceability
- Characterization of as-built samples and evolution through heat treatments to select optimal heat treatment cycle (HIP baselined)
 - Partnership with Auburn NCAME
- After appropriate heat treatment cycle, complete temperature dependent tensile and fatigue testing
- Partial data set will be published as an appendix in upcoming AIAA book on AM
- All data will be published in a handbook and raw data uploaded to selected database (potentially MAPTIS)





AM Technology Maturation Electron Beam Freeform Fabrication (EBF3)



Ground-Based System for Large Structural Components

- Electron beam melts pool on substrate, metal wire added to build up parts in vacuum environment
- Large build volume (72" x 48" x 24") and high deposition rates (3 to 30 lbs/hr) possible with lower resolution for parts that will be finish machined
- Dual wire-feed and free-standing, 6-axis part manipulation enables functional gradients and addition of details onto simplified preforms
- Alloys deposited include aluminum (2219, 2139, 2195), stainless steel (316), nickel (In625, In718), titanium (Ti-6-4, CP Ti), copper

Portable Systems for In-Space Simulation Experiments

- First successful microgravity demos February 2006
- Microgravity tests support fabrication, assembly and repair of space structures and in-space manufacturing of spare parts
- Smaller build volume (12" x 12" x 12") with finer wire for more precise deposits minimizing or eliminating finish machining
- Two systems designed and integrated in-house to assess different approaches for reducing power, volume and mass without impacting build volume

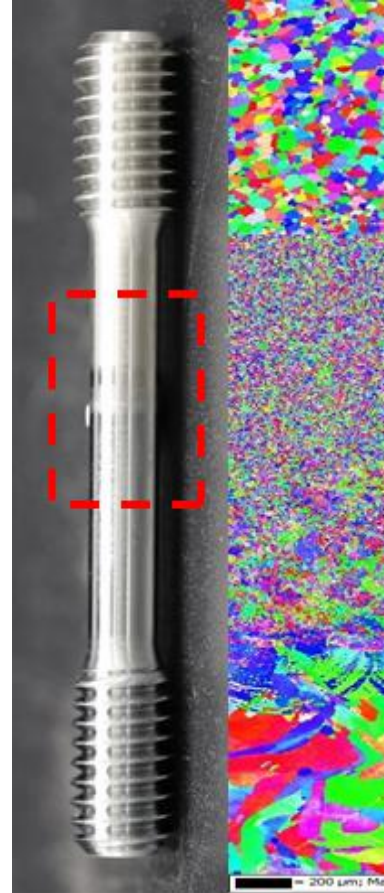




AM Technology Maturation Jet Propulsion Lab



- Additive hardware on Mars 2020 (Planetary Instrument for X-ray Lithochemistry)
 - Used tenets similar to NASA 6030
 - Structural components are EB-PBF Ti-6Al-4V
 - Non-structural components (covers) are L-PBF AlSi10Mg
- JPL qualifying L-PBF Al 6XRAM2 and Ti-6Al-4V to QMP-A per NASA-STD-6030 on EOS M290s
- Developing gradient alloy systems using Laser DED for potential inclusion on the Sample Return Lander



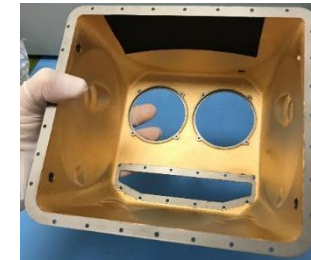
Gradient alloy sample, with EBSD plot of gradient region



X-ray bench and support



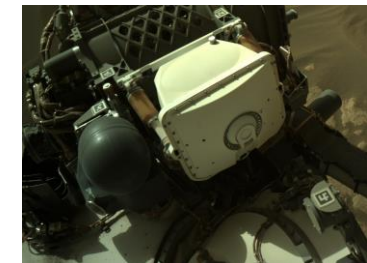
Mounting frame



Back cover



Front cover

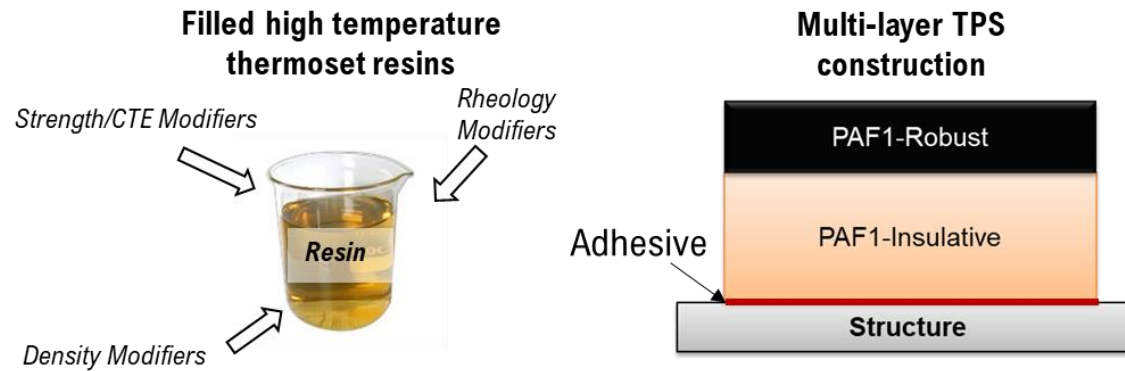


PIXL in service on Mars, image courtesy NASA/JPL-Caltech

AM Technology Maturation

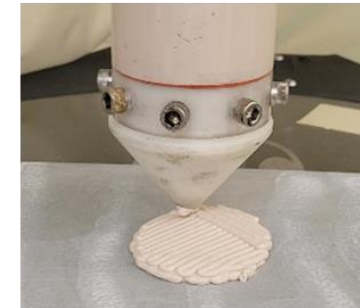
AM Thermal Protection System Development

Material development

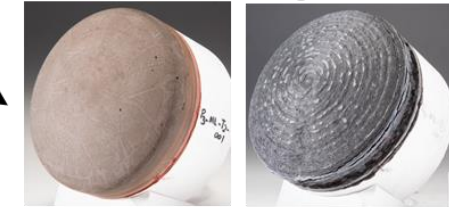


Material evaluations

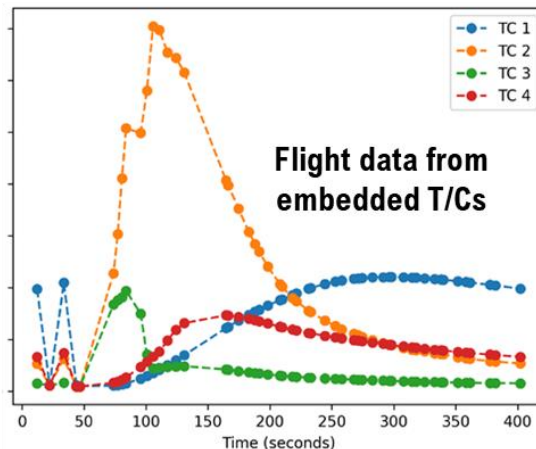
Print



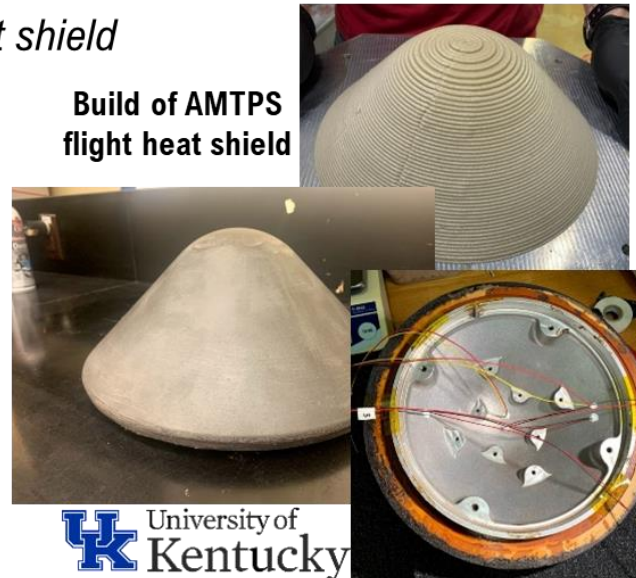
Thermal Testing



Flight testing of an AMTPS heat shield



Build of AMTPS flight heat shield



Process scale-up

Large scale robotic AMTPS system under development at Oak Ridge National Lab





AM Technology Maturation STRI Space Tech Research Grants Proposal Call

The goal of the institute is to conduct ground-breaking interdisciplinary research to exploit new advancements in computational tools in concert with experimentation to advance the use of model-based tools for accelerated certification of critical additively manufactured aerospace products.

1. Further the understanding of materials-processes-structure-property relationships for AM through integrated computational materials engineering (ICME), materials genome initiative (MGI), and other model-based approaches.
2. Demonstrate uncertainty quantified physics-based models and simulations to understand the factors that can affect the formation, distribution, and effects of process-induced defects and address other principal sources of variability.
3. Integrate and apply methodology, software tools, artificial intelligence and machine learning, and databases based on computational and experimental tools to a model-centric certification approach via digital twins.
4. Educate, Train, and Connect the Materials and Manufacturing R&D Workforce to promote US economic competitiveness and leadership in space and grow a world-class AM workforce.

Award Information - Preliminary Proposals Closed on 8.3.2022

- Expected duration: **5 years**
- Award amount up to **\$3M per year** (\$15M over 5 years)
- Award instrument: grants to U.S. universities
- Low to mid TRL
- Institutes expected (and *empowered*) to implement their own review internal processes
- NASA oversight – annual reviews and brief quarterly status reports



AM Technology Maturation Space Technology Research Grants Early Innovation Awards

ESI20 – Year 2 to Year 3 Continuation Advancement of Additive Manufacturing Techniques for High Temperature Materials	INSTITUTION
Efficient Alloy and Process Design for Additive Manufacturable Refractory Alloys	Texas A&M University
Design of Refractory Alloys for Processing by Additive Manufacturing and Service at Extremely High Temperatures	Carnegie Mellon University
Conventional and Flash Sintering of Tungsten and Tungsten Alloys Prepared by Robocasting of ALD-doped Precursors	University of Colorado, Boulder



AM Technology Maturation In-Space Manufacturing (ISM)



On-Demand Manufacturing & Recycling of Plastics

- 3D printing and recycling system designed to repeatedly recycle plastic materials into feedstock for additive manufacturing in the microgravity environment of the ISS.

On-Demand Manufacturing of Metal

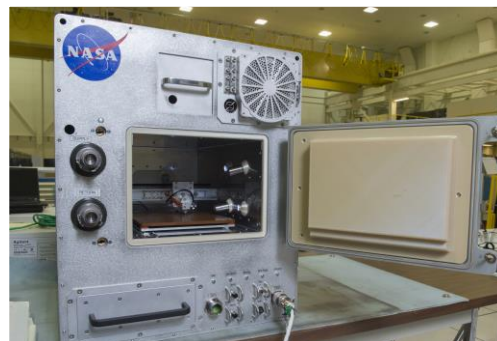
- Additive and subtractive manufacturing systems for creating metal parts on demand.

On-Demand Manufacturing of Electronics

- Ability to fabricate electronics during missions, such as crew and structural monitoring systems and sensors.



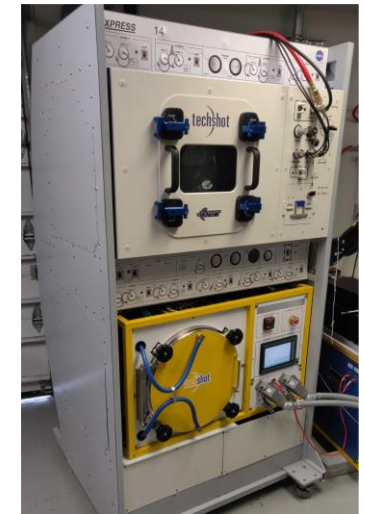
*First 3D printer in space, 2014
ISS Demonstration*



*Refabricator ISS
Demonstration*



*Redwire Commercial ISS Additive
Manufacturing Facility (AMF)*



*Techshot Fabrication
Laboratory*

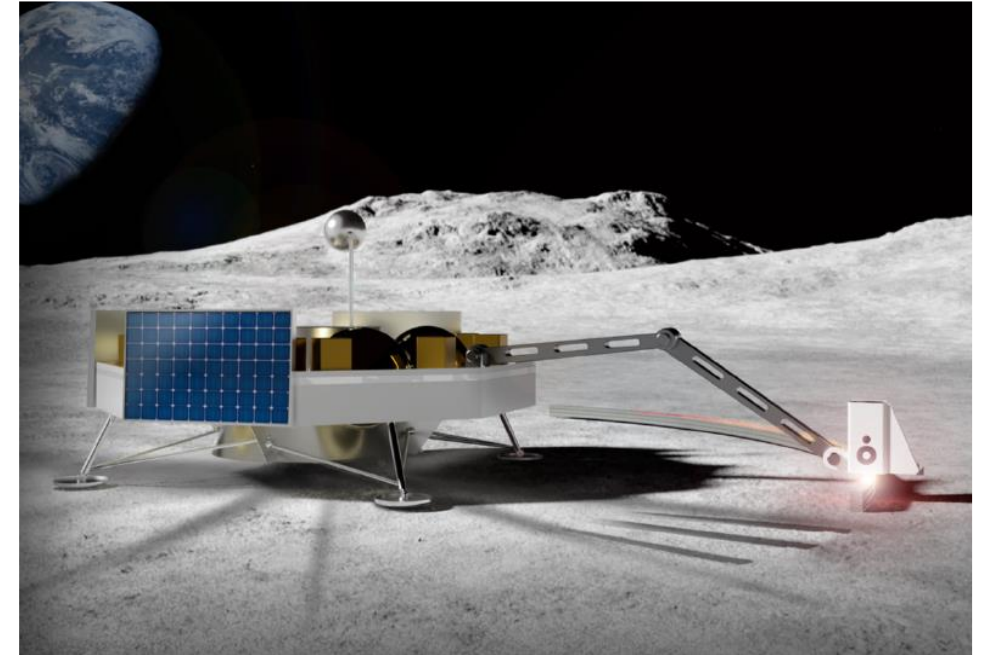


AM Technology Maturation



Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT)

- **Develop, deliver, and demonstrate capabilities to:**
 - Protect crew and hardware
 - Build infrastructure
 - Construct landing pads, habitats, shelters, roadways, berms and blast shields using lunar regolith-based materials
 - Candidate methods include both cementitious and straight regolith (melting) methods



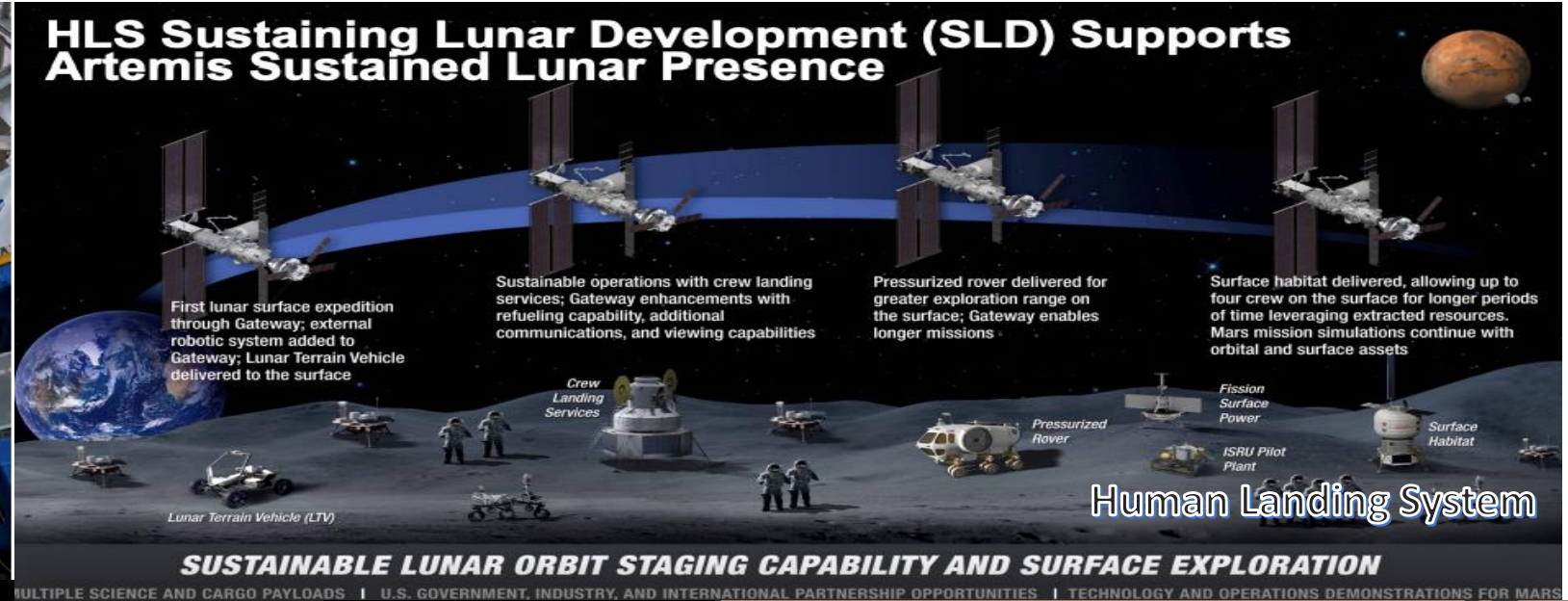
Demonstration Mission, DM-1 (~2026)



Spaceflight AM Certification Active Flight Program Support



Space Launch System



Lunar Gateway



Orion



Commercial Crew



Robotic Exploration



Spaceflight AM Certification Collaborations



Carnegie Mellon University

NASA University Leadership Initiative at Carnegie Mellon University on *Development of an Ecosystem for Qualification of Additive Manufacturing Processes and Materials in Aviation*
(6 universities, 2 small businesses)

Focused on development of defect-based process maps that guide AM production machine settings to minimize or eliminate those manufacturing defects.

→ **Process Windows to Guide AM Machine Settings**



Transformation Tools and Technologies Project's effort on *Qualification and Certification of Advanced Manufacturing-Based Materials and Structures*

Focused on understanding the effect of processing on evolution of material microstructure and defects and the resulting effects of microstructure and defects on lifecycle performance

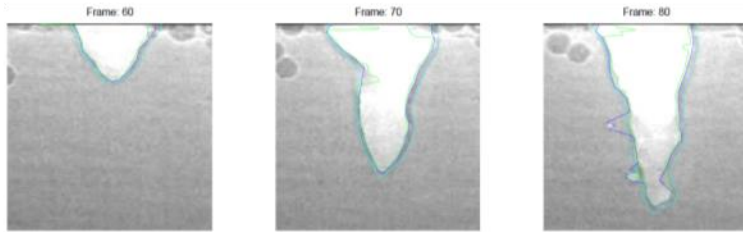
→ **Microstructurally-Informed Durability and Damage Tolerance**



Spaceflight AM Certification Transformational Tools and Technologies Project

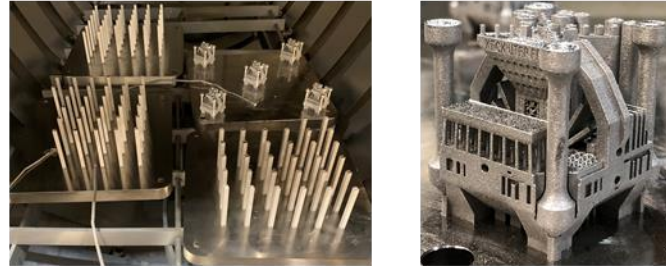


Data Science



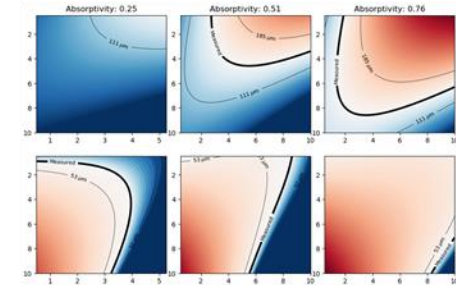
Automated vapor depression
boundary identification using
machine vision

PSP Round Robin



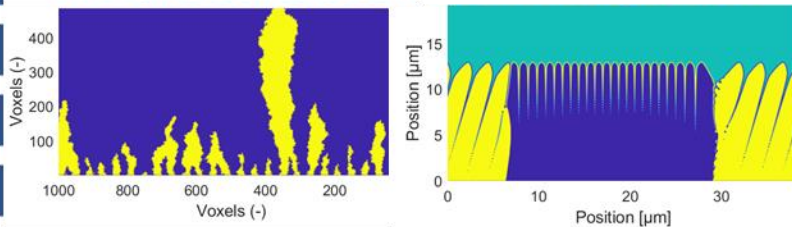
Process structure property (PSP)
round robin for laser powder bed
fusion machine variability

Thermal Simulation



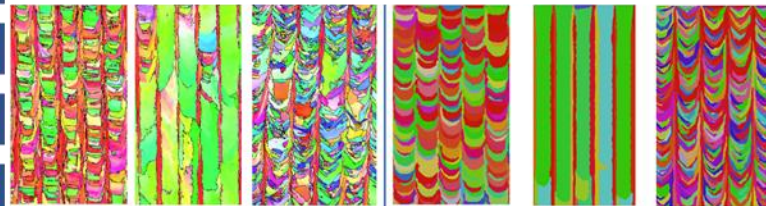
Efficient and flexible probabilistic
calibration of finite element (FEM)
process models using measured data

Multi-Fidelity Microstructure Simulation



Crystallographic texture evolution
modeling through joint Monte Carlo
& Phase Field simulations

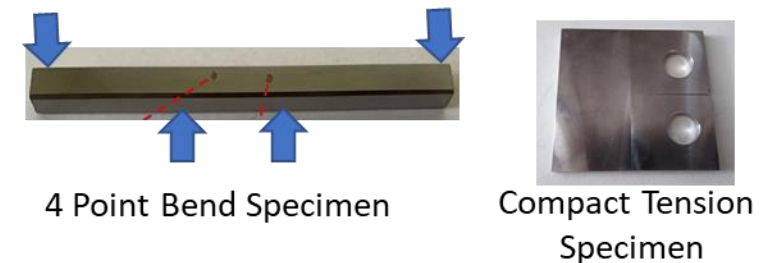
Microstructure Simulation and Validation



Experiment Simulation

Simulated grain shapes and
textures compared with experiment

Mechanical Testing



4 Point Bend Specimen Compact Tension
Specimen

Understanding the effects of
processing defects on fatigue crack
initiation and propagation



Spaceflight AM Certification

Agency-wide AM Cert support Team (AACT)

- **Need for AACT:** There is no formal and “institutionalized” group, no formal authority for technical integration across agency, scattered and sporadic support to high-risk programs.
 - Missed opportunity for knowledge advancement and gap closure, everyone needs it but no one program could fund it.
 - Education of NASA workforce and SMEs; hinderance to being a smart buyer.
 - Technical hurdles for AM certification remain significant
- **Goal:** Enabling AM adoption as safely as possible without additional barriers
 - Develop Smart Buyer NASA workforce to ensure sustainable agency-wide AM Certification
 - Advocate for critical AM tech advancement and capabilities across the agency, cross agency risk reduction
 - Provide centralized leadership for AM technical integration across agency
- **Near-Term Objective:**
 - Work risk mitigation/capability enhancing projects to close gaps in current certification knowledge
 - Form AM SME competency development program (OJT training, mentoring, external engagement)
 - Train them to be, and be recognized as, the go-to experts
 - Continue supporting programs with critical AM qual/cert activities



Spaceflight AM Certification

Fracture Control Framework for AM Parts

- Fracture control is reliant on understanding the design, analysis, testing, inspection and tracking of hardware.
 - The adaptation of state-of-the-art AM technologies introduces new and unique challenges
 - e.g. Multiple lasers and adaptive technologies
 - For AM applications the application of conventional NDE techniques is questionable
 - There is a need to produce alternate approaches through the adaptation of a Probabilistic Damage Tolerance Approach (PDTA)
 - Computational modeling for AM
 - Understanding the “Effects of defects”
 - In-situ monitoring and inspection
- These items
MUST
Work
together not
separate



Spaceflight AM Certification Computational Modeling of AM



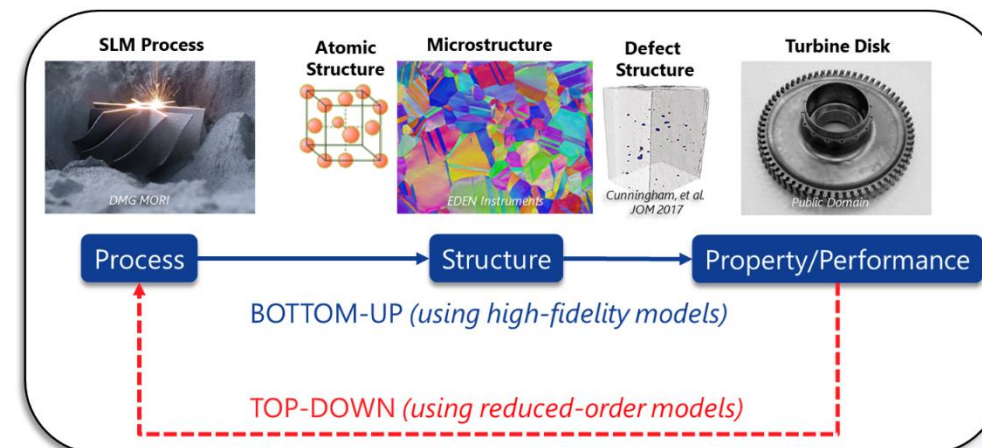
- Two aspects of qualification and certification to consider:
 1. Design Certification
 - Demonstration that design meets all the requirements of the defined mission
 2. Hardware Certification
 - Demonstration that the hardware meets all the requirements of the certified design
- Opportunities for computationally-assisted qualification and certification
 - Focus primarily on augmenting the existing qualification and certification processes, NOT replacing them
 - Such methods fit into current NASA AM requirements
 - Such tools will require verification and validation
 - Leverage government-industry partnerships

APPLICATION OF PSP MODELING FRAMEWORK **Integration within AACT**

Adapt validated high-fidelity models for higher TRL applications

- **Reduced order model approaches**
 - Quickly predict performance metrics from defect content
 - Reduce the process parameter space based on design specifications
- **Uncertainty quantification framework**
 - Bound probability of detecting crack initiating defects in fatigue

Open to dialogue for integration of tools within AACT





Spaceflight AM Certification

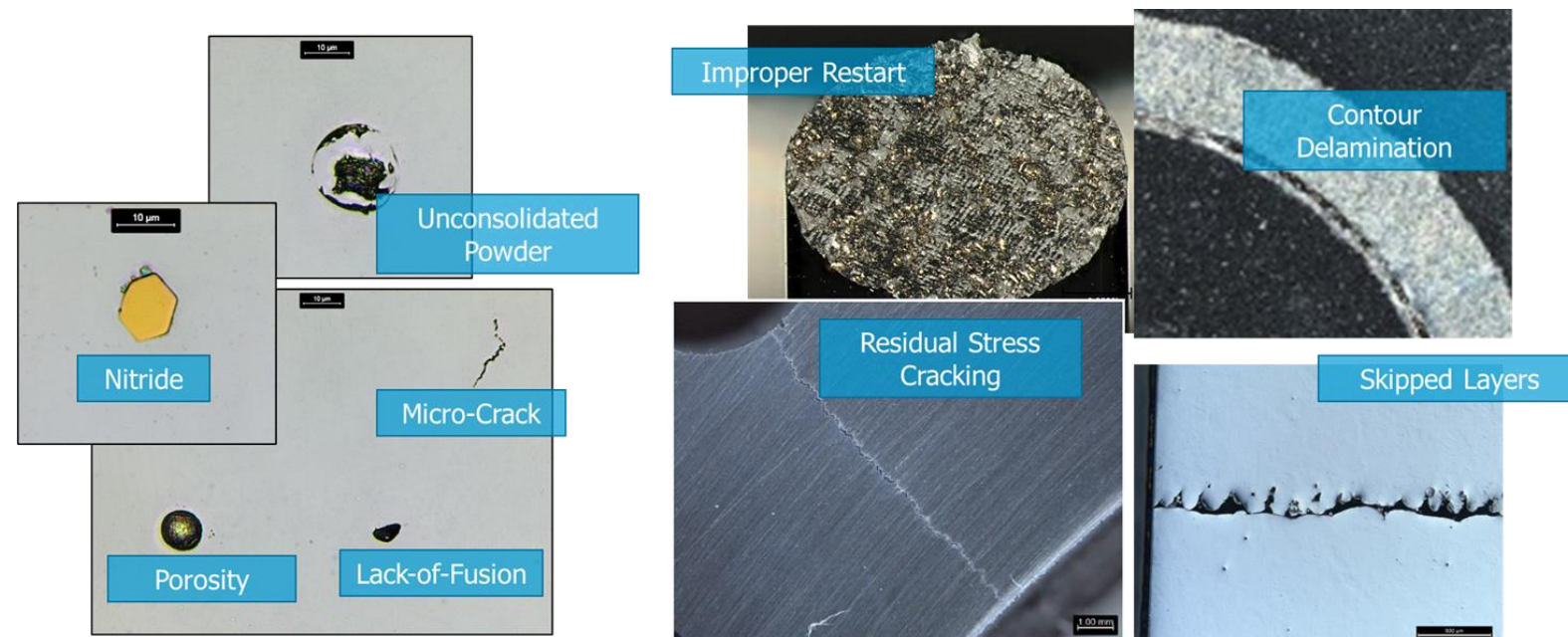
Effects of Defects



Flaws in AM fall into two categories

1. **Inherent flaws** – Flaws that are representative of the characterized nominal operation of a qualified AM process.
2. **Process Escape flaws** – Flaws that are not representative of the characterized nominal operation of a qualified AM process.

- **Flaw** – an imperfection or discontinuity that may be detectable by nondestructive testing and is not necessarily rejectable.
- **Defects** – one or more flaws whose aggregate size, shape, orientation, location, or properties do not meet specified acceptance criteria and are rejectable.



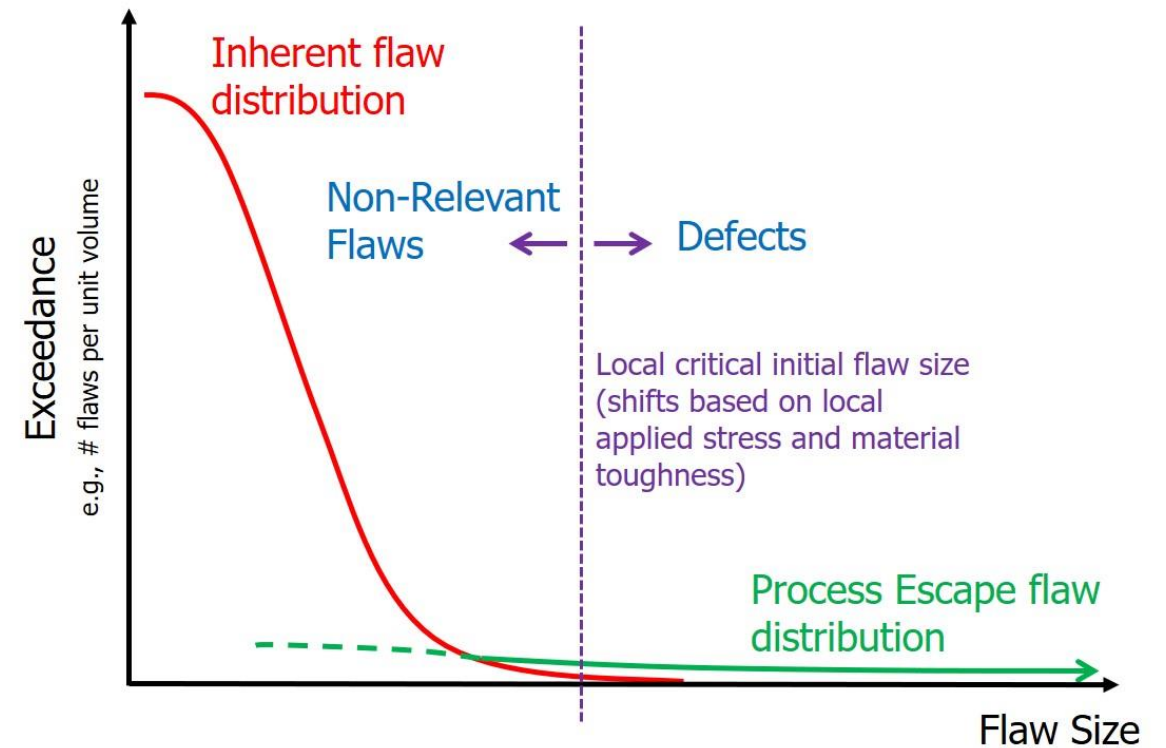


Spaceflight AM Certification

Effects of Defects



- Phase 1: Understanding inherent defects
- Phase 2: Using process controls to control inherent defect populations
- Phase 3: Understanding Rogue (process escape) defects





Spaceflight AM Certification In-Situ Monitoring



- NASA-STD-6030 requires
 - Quantitative NDE for class A parts
 - NDE for process control for class B parts
 - In-situ monitoring must be qualified in manner analogous to other NDE techniques
- Two main functions of in-situ process monitoring:
 - Process Control
 - Real-time warnings of build problems
 - Check for process drift
 - Monitor effects of parameter changes
 - Part Quality
 - Quantitative analysis
 - Requires correlations between indications, physics of the process and actual defects
 - Need to know probability of detection

} Must meet requirements of NASA-STD-5009



Spaceflight AM Certification In-Situ Monitoring

- Challenges to using in-situ monitoring:
 - Indirect defect observations will require an understanding of the physics
 - Current certification approach requires a locked process
 - For real-time changes a new approach is needed
 - Current certification approach does not accommodate the use of adaptive systems
 - Creates two issues for verification
 1. Verify the sensor performance, algorithm and machine response (control system)
 2. Verify the physics – does controlling this parameter result in a good part?



Spaceflight AM Certification

In-Situ Monitoring NASA/ASTM Workshop



- NASA sponsored a workshop focused on in-situ technology readiness for application in AM qualification and certification June 28-29, 2022.
- The workshop was run by the ASTM AM CoE
- Objectives
 - Middle-to-high technology readiness level (TRL) in situ technologies that show promise for near-term use
 - Approaches to qualification of in situ methods for use as a quality assurance tool in critical applications
 - Methods for integrating in situ data in AM production including real-time detection and closed-loop control
 - Standardization gaps, key challenges, and research & development needs
- Day 1 included 9 technical talks and a panel discussion
- Day 2 included breakout sessions
 - Topic 1: Technical Development/Maturation
 - Topic 2: Types of Detectable Defect States
 - Topic 3: Data/Defect Correlation
 - Topic 4: Real-Time Detection & Closed-Loop Control
 - Topic 5: Standards



Event outcome = Public Roadmap



Credits



- Corky Clinton
- Brian McEnerney
- Ed Glaesseggen
- Andrew Glendening
- Paul Gradl
- Mallory James
- Omar Mirales
- Alison Park
- Karen Taminger
- Will Tilson
- Brian West
- Doug Wells
- John Vickers



Questions?

