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Adaptation of Metal Manufacturing Systems for the International Space Station (ISS)

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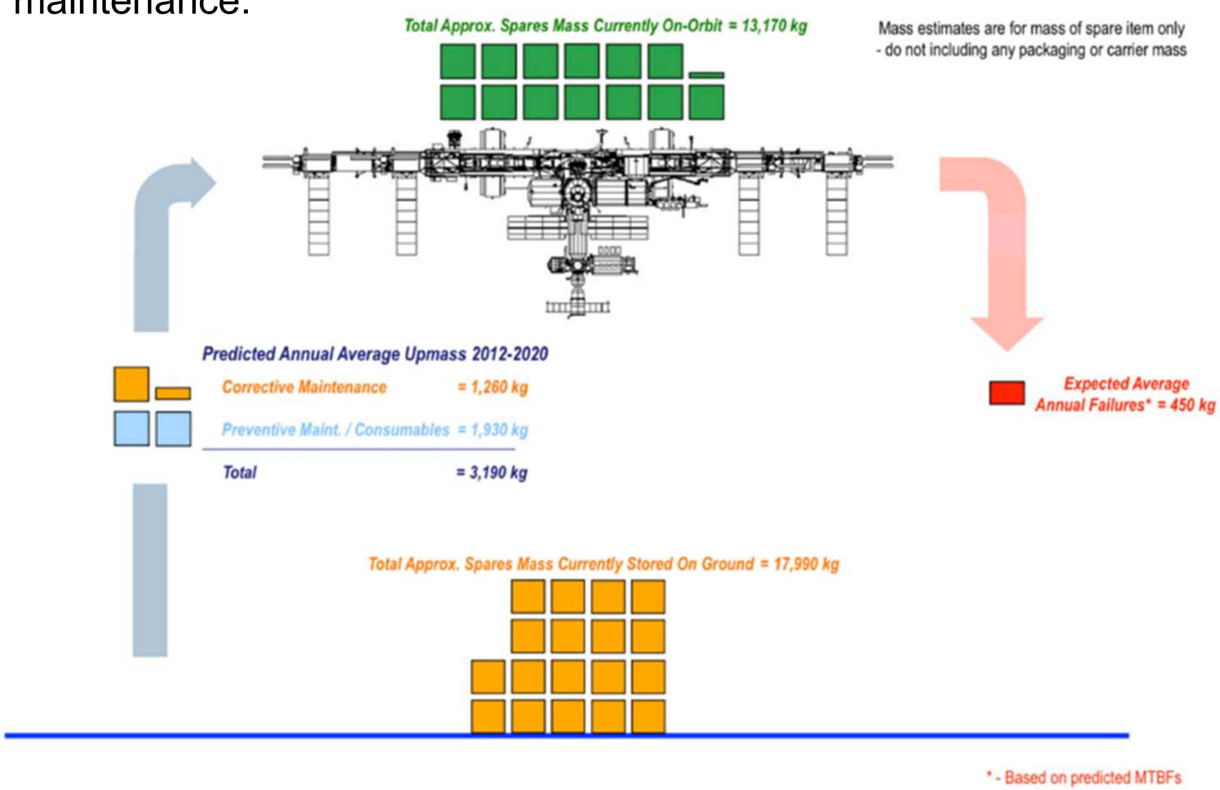
About Me

Tracie Prater is an engineer in the Materials and Processes Laboratory at NASA Marshall Space Flight Center in Huntsville, Alabama, where she is currently the lead for the on-demand manufacturing of metals (ODMM) element of the in-space manufacturing (ISM) project. She also serves as a subject matter expert for NASA's Centennial Challenges prize competition program in materials and manufacturing and helped to develop the 3D Printed Habitat Challenge. She has a B.S. in Physics from Eastern Kentucky University and an M.S. and Ph.D. in mechanical engineering from Vanderbilt University. Tracie is also a senior member of the American Institute of Aeronautics and Astronautics.

The International Space Station (ISS) Logistics Model

The ISS is heavily dependent on Orbital Replacement Units (ORUs) for system-based repair and maintenance.



Historical incidence of system failure and use of spares per year (based on 2016 analysis) is 450 kg, which is 3.4 percent of the total spares stored on ISS.

Cirillo, W., Aaseng, G., Goodliff, K., Stromgren, C., and Maxwell, A., Supportability for Beyond Low Earth Orbit Missions," AIAA SPACE 2011 Conference & Exposition, No. AIAA-2011-7231, American Institute of Aeronautics and Astronautics, Long Beach, CA, Sep 2011, pp. 1-12.

On-Demand Metal Manufacturing (ODMM)

The On-Demand Metal Manufacturing project seeks to address the unprecedented challenges associated with prepositioning of spares on long endurance missions:

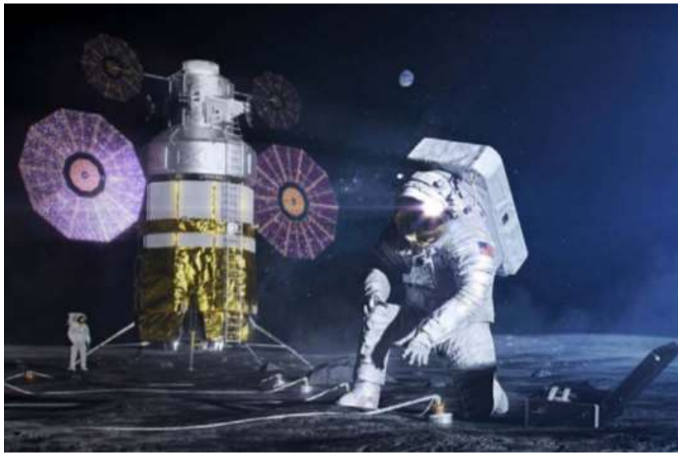
- Storage space for spares will be more limited relative to ISS
- Cargo resupply opportunities are also more limited
- Crew safety and responding to unforeseen scenarios

The pressurized volume of ISS is 1,218 cubic meters (43,000 cubic feet).

ODMM Project Objectives

- Work with commercial partners to deliver flight-certified, on-demand manufacturing systems to ISS
- Demonstrate on-demand manufacturing approaches for metals in a microgravity, crewed environment
- Evaluate materials and parts made on ISS relative to ground-manufactured specimens
- Develop physics-based models to understand materials, processes, and material outcomes under low gravity conditions

Astronaut Butch Wilmore with a 3D printed polymer part on ISS in 2014. ODMM is the next step for manufacturing in space.



ODMM is an enhancing capability for operations on the lunar surface, in orbital platforms, or transit habitats.

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ODMM Part Database

- The ODMM part database consists of candidate parts for manufacturing on space missions
- Parts are derived from environmental control and life support systems (ECLSS), crew tools, medial toolkit, communications systems, electrical power systems, and other payloads
- Most frequently used materials for ISS systems are Aluminum alloys, Titanium and Stainless Steel
- 50% of parts from ECLSS spares will fit within a 150 mm x 150 mm x 150 mm build volume

Extravehicular Activity (EVA) tools ready for flight.

Urine Processor Assembly (UPA) for ISS.

Challenges in Adapting Additive Manufacturing Systems to ISS

- Scale/scalability of hardware
  - Power (maximum power draw for a payload is 2000W)
  - Mass
  - Volume (maximum volume a system can occupy is an ISS rack, which is 0.45 m^3)
- Safety (feedstock material management, chip debris capture if post-processing involves machining)
- Limited crew interaction
- Remote commanding
- Range of materials within processing capability
- Ability to produce complex features
- Surface finish
- Build rate
- Operation in microgravity
  - Physics of deposition
  - Impact on material quality
  - Management of heat in absence of natural convective cooling
- Feedstock form, life, and storage

Image of an EXpedite the PRocessing of Experiments to Space Station (EXPRESS) Rack for ISS payloads. Image from NASA.

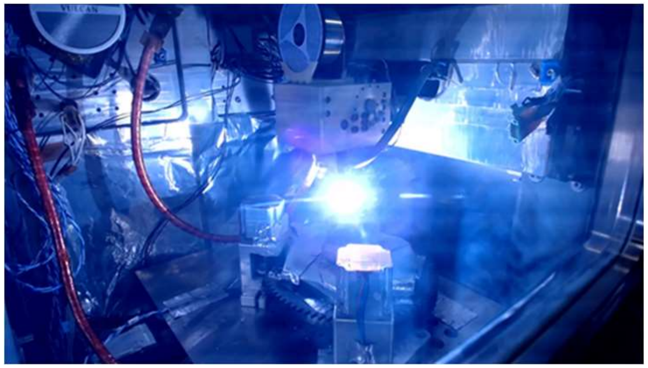
Hybrid Additive Manufacturing Systems for ISS: Vulcan from Made in Space

- Wire+arc additive manufacturing (WAAM)
  - electric arc as a heat source and wire as a feedstock
  - deposition process occurs in an enclosed chamber with an inert shielding gas
- As-printed part requires machining to obtain net shape
  - Debris generated is fully captured by an environmental control unit
- Vulcan can also manufacture with polymers using fused filament fabrication (weldhead can be changed out as an ORU)

Steps in the Vulcan hybrid AM process: additive manufacturing via WAAM, subtractive manufacturing, and net shape part. Image from Made in Space.

Vulcan subsystems

- arc welding system for deposition of metal material
- a Computer Numeric Control (CNC) mill with automated changeout of tools via a carousel
- a chip capture system/environmental control unit
- an iris clamp
  - provides a grounding path for welding operations, holds the build plate, and fixtures the part)
- a robotic gripper
  - reorients the part as needed for machining and separation from the build plate
- ORU for polymer manufacturing



Vulcan Engineering Development Unit in operation (additive manufacturing). Image from Made in Space.

CAD rendering of Vulcan EDU. Image from Made in Space.

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In-process monitoring

- Traditional approaches to part certification will be difficult to adapt for future space missions
  - Currently ground-based part certification for AM relies on full volumetric inspection
- Prior work by Made in Space developed *Amaru*, an in-process monitoring system for Vulcan
  - Real-time monitoring and classification of layer quality

Training Amaru using weld beads deposited at various process parameters. Welded samples were purposely created at varying levels of quality to train the system to identify unacceptable welds. Image from Made in Space.

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Vulcan maturation

- Vulcan is continuing maturation toward a flight demonstration mission
  - Parabolic flight campaign planned for 2021
  - Production of extensive set of specimens and parts for characterization with EDU
  - Design of flight system
  - Continued interaction with ISS on payload requirements and safety
- NASA Ames Research Center (ARC) is also developing a model of the WAAM process in microgravity

Heat sink produced with Vulcan. Image from Made in Space.

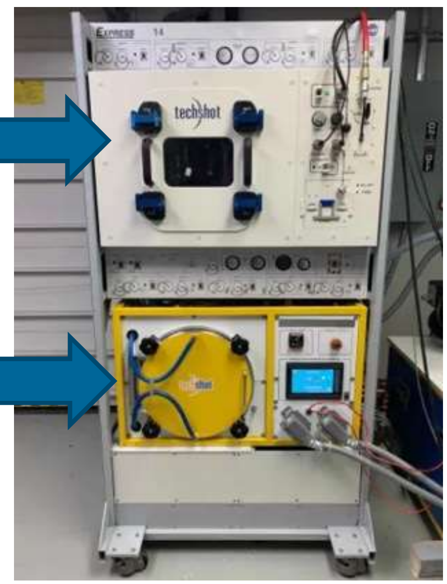
Example of part produced with Vulcan (prior to substrate removal). Image from Made in Space.

Techshot Fabrication Laboratory (FabLab)

The Techshot Fabrication Laboratory system uses bound metal additive manufacturing. The system is in the form of a full EXPRESS rack.

Print chamber: metal particles bound in a polymer are extruded and deposited on a build plate. The printing subsystem can also extrude polymers via fused filament fabrication.

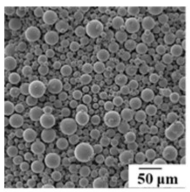
Furnace chamber: The part undergoes a de-bind cycle (to liberate the polymer binder) and the remaining metal is sintered. The part returns to the print chamber for finishing.



Ground based prototype system for bound metal additive manufacturing developed by Techshot, Inc. Image from Techshot, Inc.

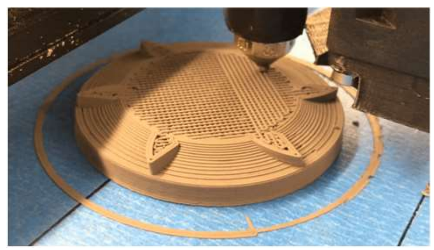
Filament Development for Techshot FabLab

Filament development work for the FabLab prototype system was performed by University of Louisville.

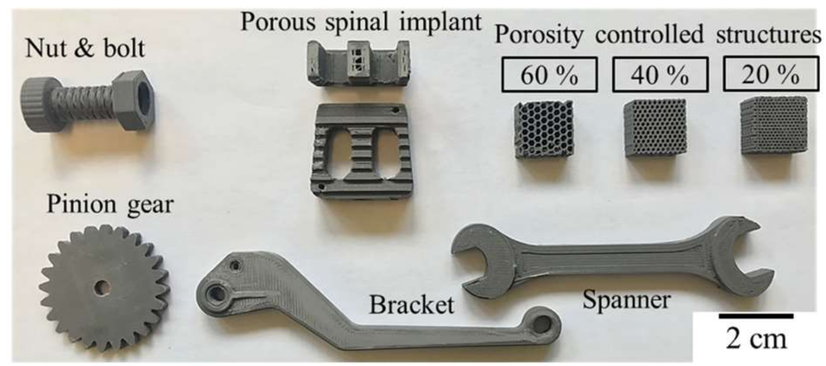


Binder

Ti-6Al-4V spooled filament (59% solid loading)



Printing of green part



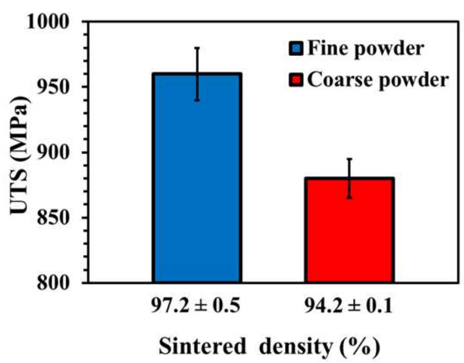
Examples of printed geometries. Image from University of Louisville.

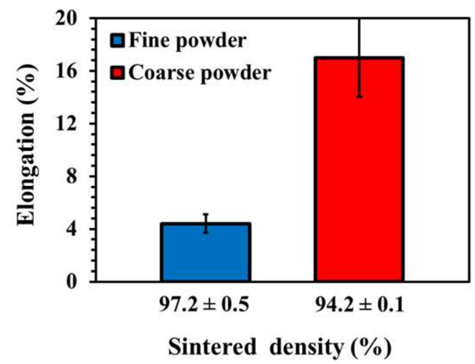
All images from University of Louisville. C. Hill, Singh, Atre, Cate, et al. "Metal Fused Filament Fabrication of Titanium Alloy for In-Space Manufacturing." National Space and Missile Materials Symposium. June 2020.

Results of Filament Testing

Particle size impacts the density, ultimate tensile strength (UTS), linear elongation to failure of BMD parts. Coarse and fine powders also have different starting oxygen contents.

Parts Sintered at 1250° C for 4 hours





Starting powder	Coarse	Fine
Oxygen	0.08%	0.16%
Diameter (50th percentile)	30 um	13 um

All images from University of Louisville. C. Hill, Singh, Atre, Cate, et al. "Metal Fused Filament Fabrication of Titanium Alloy for In-Space Manufacturing." National Space and Missile Materials Symposium. June 2020.

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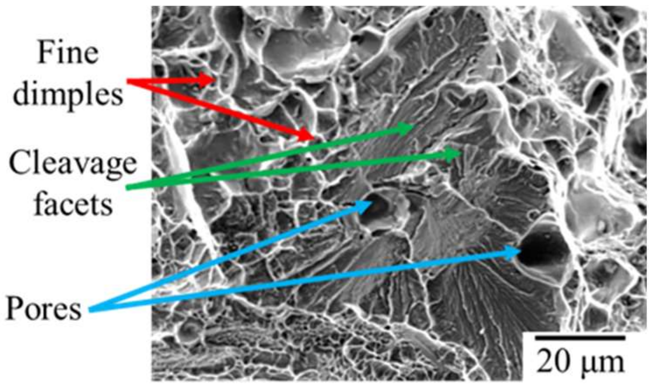
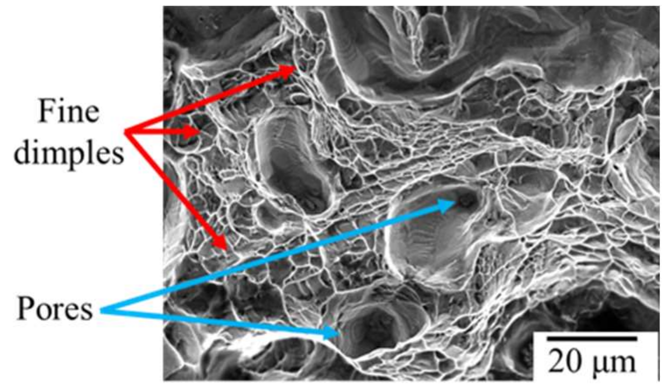
Microstructure

The images below illustrate the relationship between particle size and fracture behavior for materials printed with the Ti-64 filament.



Fine powder samples exhibit brittle fracture with surface dominated by cleavage facets.



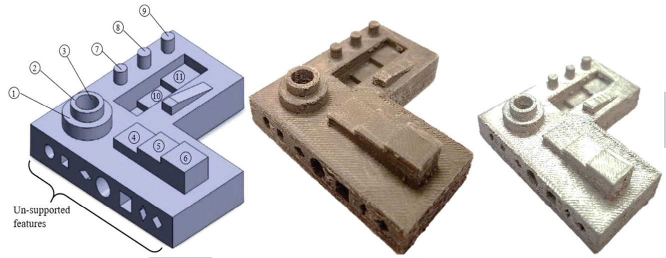
Coarse powder samples show ductile fracture with the presence of fine dimples.

All images from University of Louisville. C. Hill, Singh, Atre, Cate, et al. "Metal Fused Filament Fabrication of Titanium Alloy for In-Space Manufacturing." National Space and Missile Materials Symposium. June 2020.

Model of bound metal additive manufacturing process

Problem formulation

- Modeling of manufacturing processes in microgravity is challenging
- This modeling activity focused on a specific issue - nonlinear shrinkage of the printed parts -- in bound metal additive manufacturing. This phenomenon makes it difficult to manufacture parts with accurate dimensions.
- The related physics scales span from atomistic through the mesoscale.
- To analyze and find methods of mitigating shrinkage, NASA Ames Research Center developed a set of self-consistent models that allow simulation of material shrinkage during bound metal additive processing.

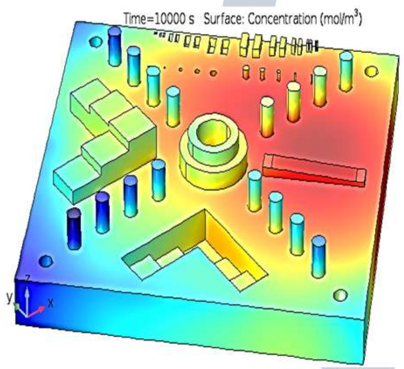


Example of nonlinear shrinkage for NIST standard item manufactured using bound metal additive manufacturing.

The results of experimental estimation of nonlinear shrinkage in NIST test item

Table II. Shrinkage of artifact part

Shrinkage		
FOI	x–y	z
#1	14%	23%
#2	18%	20%
#3	18%	–
#4	13%	22%
#5	16%	22%
#6	17%	19%
#7	13%	23%
#8	13%	23%
#9	13%	23%
#10	–	18%
#11	–	15%



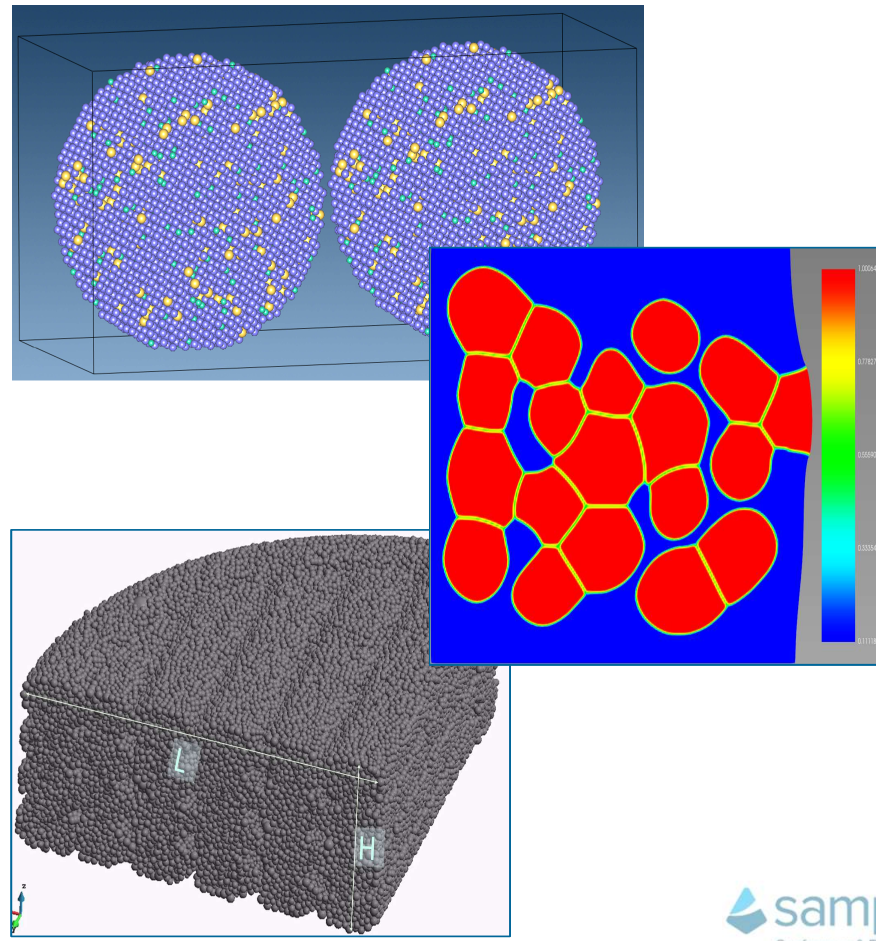
COMSOL simulations of the shrinkage in a Ti-64 part manufactured with bound metal additive manufacturing

Physical phenomena underlying sintering

Molecular dynamics. At the heart of sintering process is diffusion of atoms at the interface between two particles that includes: (i) Surface diffusion, (ii) Grain boundary and (iii) Lattice diffusion; (iv) Evaporation and condensation from the particle surface. NASA ARC used LAMMPS (https://lammps.sandia.gov/) with the Modified Embedded Atom Method potential to estimate sintering parameters including: (i) grain boundary width δ_{gb}~1 µm and diffusion coefficients. D_{surf} 8x10-10 - 1.6x10-9 m2/s.

Phase field methods describe microstructure evolution in the cross-section of one filament. NASA ARC used the phase-field module in MOOSE Multiphysics to model one of the most non-trivial steps of the sintering process that involves transformation of initially separated round particles into dense structure of grains. Researchers estimated the value of sintering stress to be a few MPa, and the time scale of sintering was in good agreement with experimental observations.

Discrete element model. To use finite element method, information to estimate the spatial mass distribution is needed. Estimation of this parameter was obtained using Discrete Element Modeling in KRATOS Multiphysics. Using this model, the initial rearrangement of the particles and the corresponding mass redistribution in small sections of the whole part (while accounting for the layout of the filaments) was estimated. The simulation had several thousand particles with diameters of approximately 50 µm.



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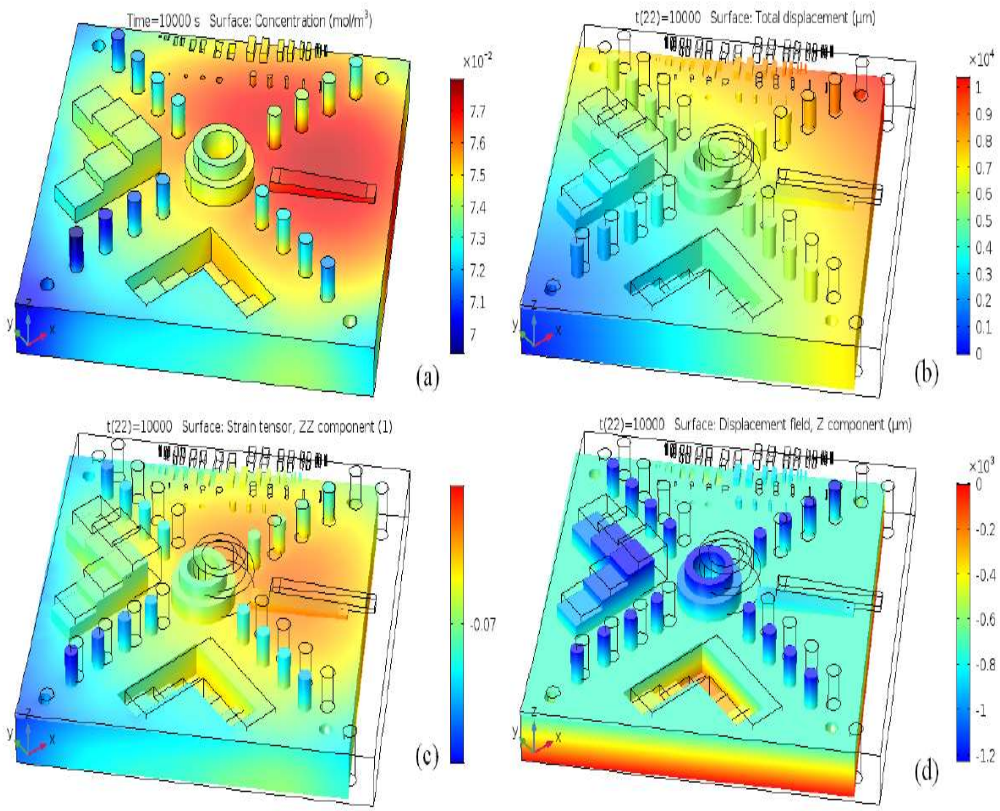
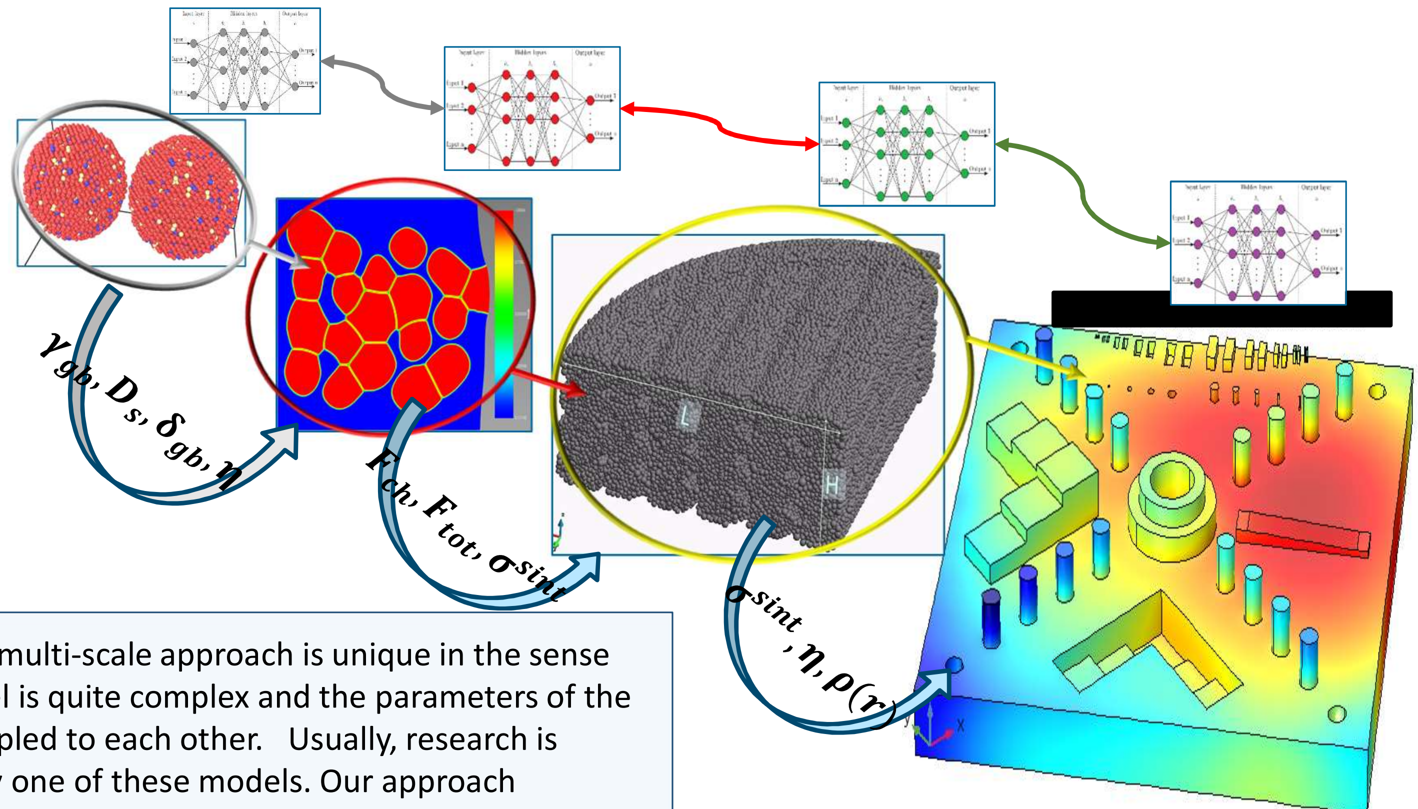
Modeling of the Computer Aided Design (CAD) Geometry

Finite element models were developed to predict anisotropic shrinkage of the whole part during debinding and sintering using COMSOL. Two macroscopic models were developed for describing the sintering process: one based on the Olevsky approach, and the second was based on shrinking the continuum due to concentration of the backbone polymer.

The model can predict anisotropic shrinkage and determine the required compensation for the green part geometry.



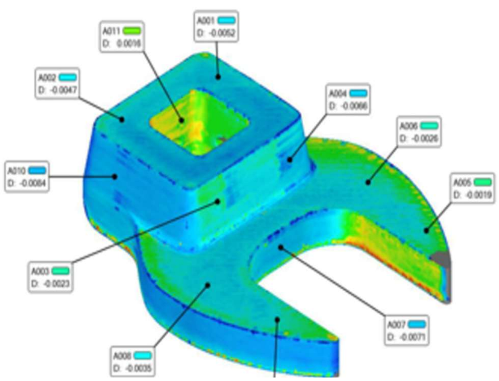
Multi-Scale Modeling Approach

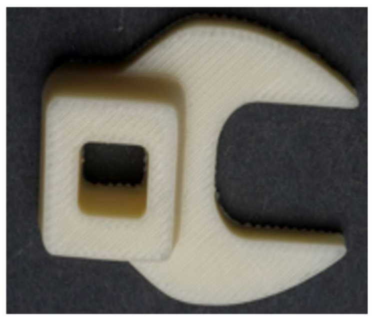


The developed multi-scale approach is unique in the sense that each model is quite complex and the parameters of the models are coupled to each other. Usually, research is focused on only one of these models. Our approach developed the set of models covering the whole spectrum of relevant physical scales coupled to each other.

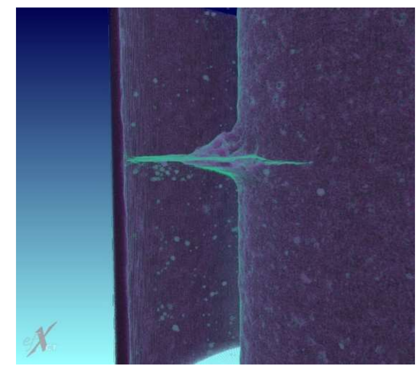
Technology Gap: On-Orbit Inspection

On-orbit inspection capabilities will be needed to verify parts produced are acceptable for use in instances where there are consequences associated with part failure.





Structured light scan from NASA Marshall Space Flight Center of crowfoot tool additively manufactured on-orbit. Colors represent deviations from the dimensions in the part file.

Future in-space computed tomography (CT) capabilities could provide both dimensional verification and volumetric inspection, including crack detection. X-ray/CT is currently the best known flaw detection technique for AM parts. Images from NASA Goddard Space Flight Center.

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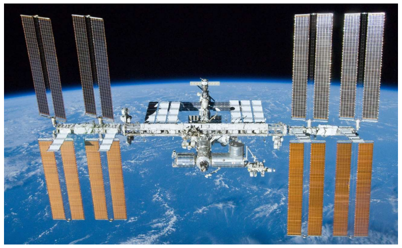
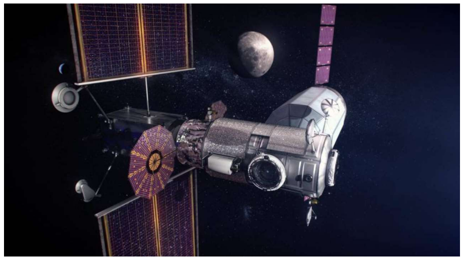
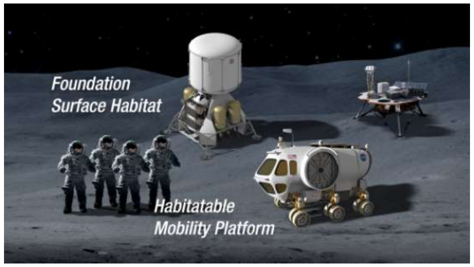
ISM Evolvability

ISM is a destination-agnostic capability and has clear mission benefits beyond low earth orbit where cargo resupply opportunities become more limited. Once tested on ISS, ISM capabilities can be infused into Gateway, lunar surface habitats, a Mars transit vehicle, or Martian surface operations.



ISS is the testbed for ISM.





ISM capabilities demonstrated on ISS are applicable to Gateway and the lunar surface.

"Houston, we have a solution."

Acknowledgments

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