Solar Additive Manufacturing with Lunar Regolith

Space Resources Round Table - June 9, 2023
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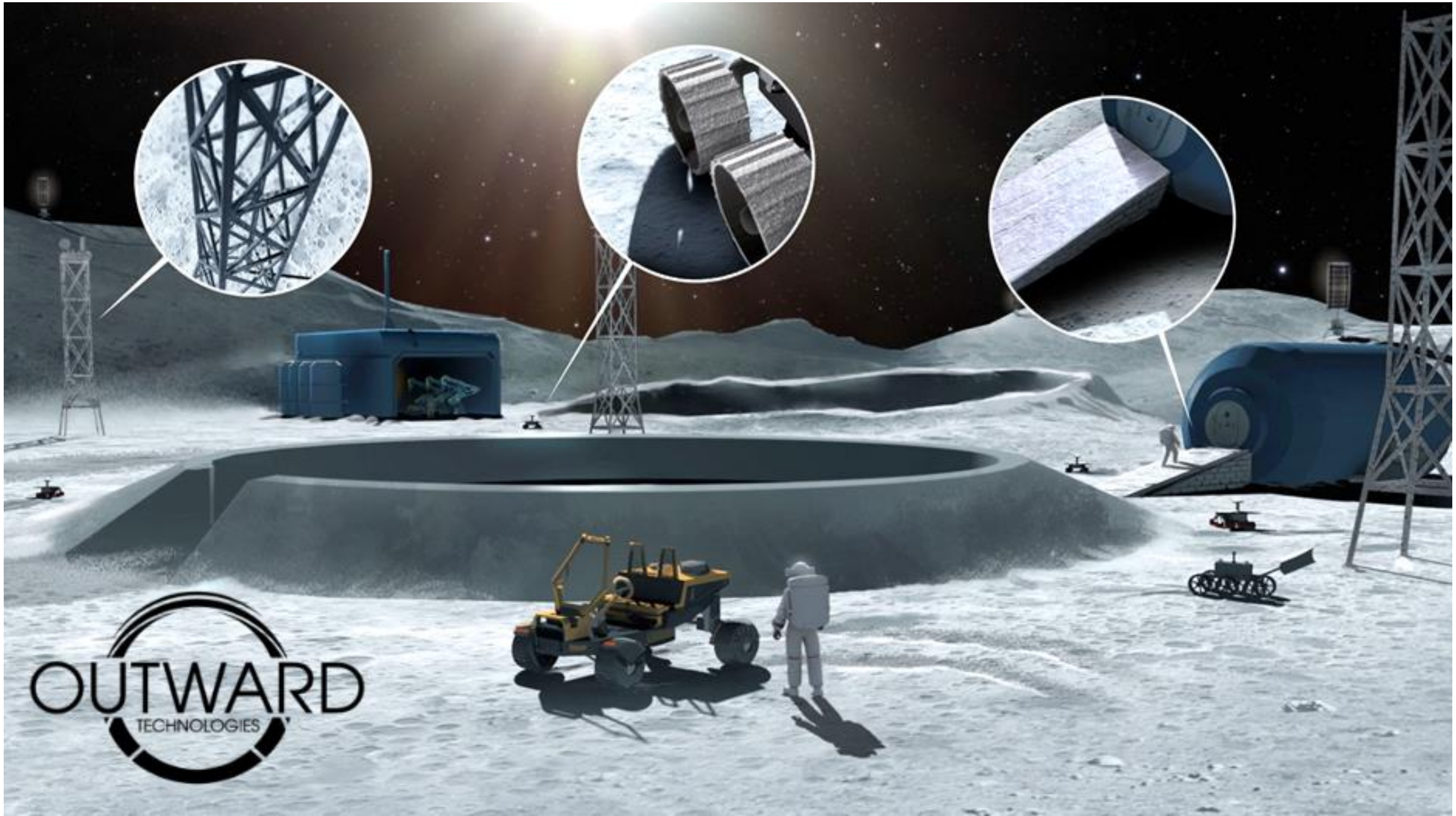
Blueshift, LLC dba Outward Technologies

Company

- **Founded 2017**
- **Mission**: To develop critical technologies for extraterrestrial mining and manufacturing
- **Philosophy**: Utilize Concentrated Solar Energy (CSE) as the heat source for various thermal processes in space to minimize electrical power requirements
- **Funding:**
  - **SBIR Phase I:** 7 NASA, 1 NSF
  - **SBIR Phase II:** 6 NASA, 1 NSF
  - **Early-Stage Capital and Retention grant through Colorado OEDIT**
- **This Work:** NSF Phase II

Vision for Solar Additive Manufacturing (SAM)

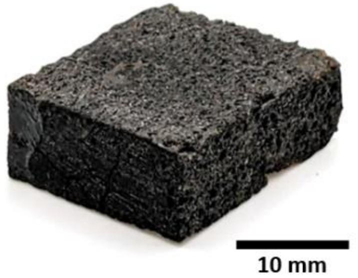
Outward's SAM system on the Moon to sell locally manufactured products.



Introduction – Solar Additive Manufacturing (SAM)

- Outward's SAM system is the first of its kind able to manufacture parts from glass, silica, metal, and lunar regolith (highlands and mare)
- Developed to TRL 4 through an NSF SBIR Phase I/Phase II project
- **Additive Processes:**
  - Primary – Powder Bed Fusion (PBF)
  - Alternative – Fused Deposition Modeling (FDM)
- **Heat Sources:**
  - Primary – Concentrated Solar Energy (CSE)
  - Alternatives – Laser (PBF), Induction Furnace (FDM)
- **Feedstock:** Lunar regolith with no binders or additives (CSM-LHT-1 simulant)
- **Recently awarded a Phase II supplement to continue development**
  - Increase build volume (1,000mm x 300mm x 100mm)
  - Additional lab-scale use-case demonstrations
- **Next steps:**
  - Parabolic flight testing to understand gravitational effects (TRL5)
  - Print in vacuum to understand thermal impacts of vacuum (TRL6)
  - Small lunar lander demonstration payload (TRL 7)
  - Full-scale lunar lander payload (TRL 8 & 9)

Post-Processed PBF Specimen



FDM Square Foundation

PBF Dovetail Rod & Connector

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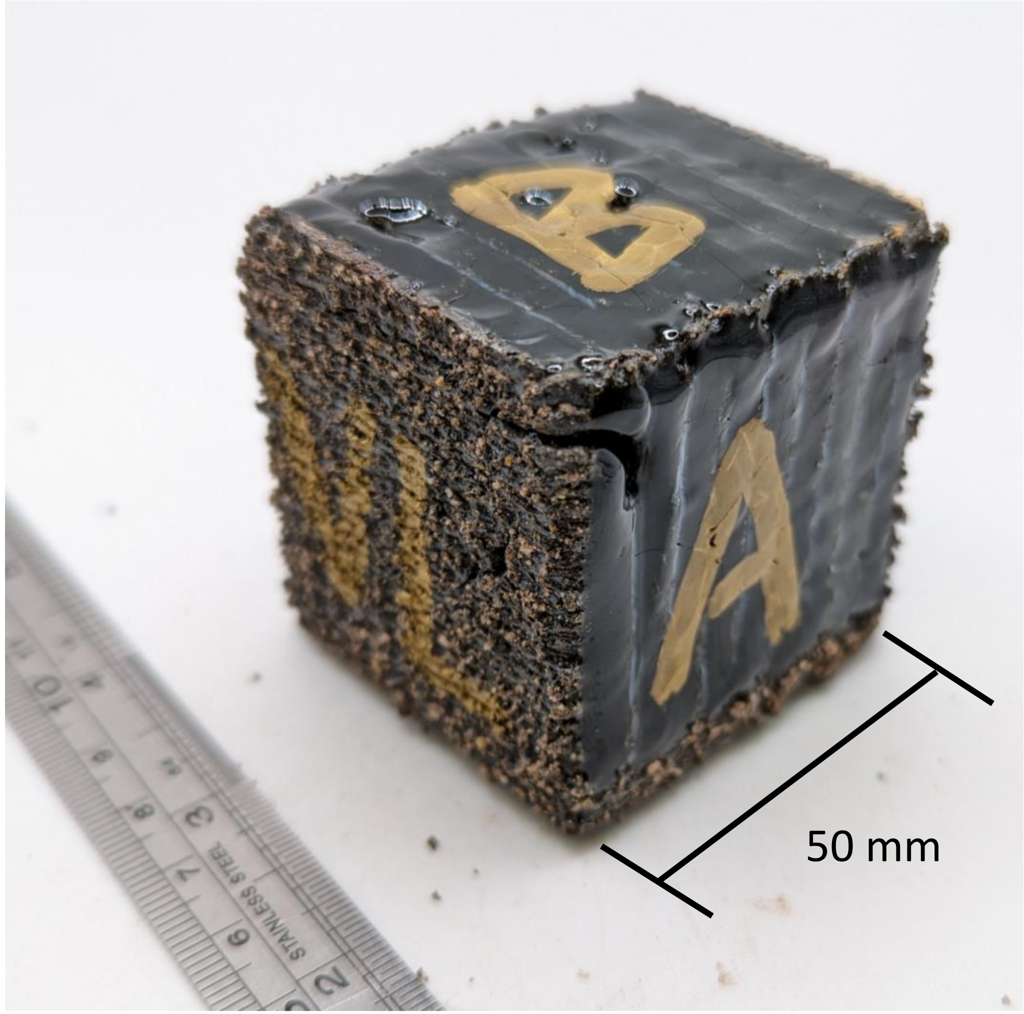
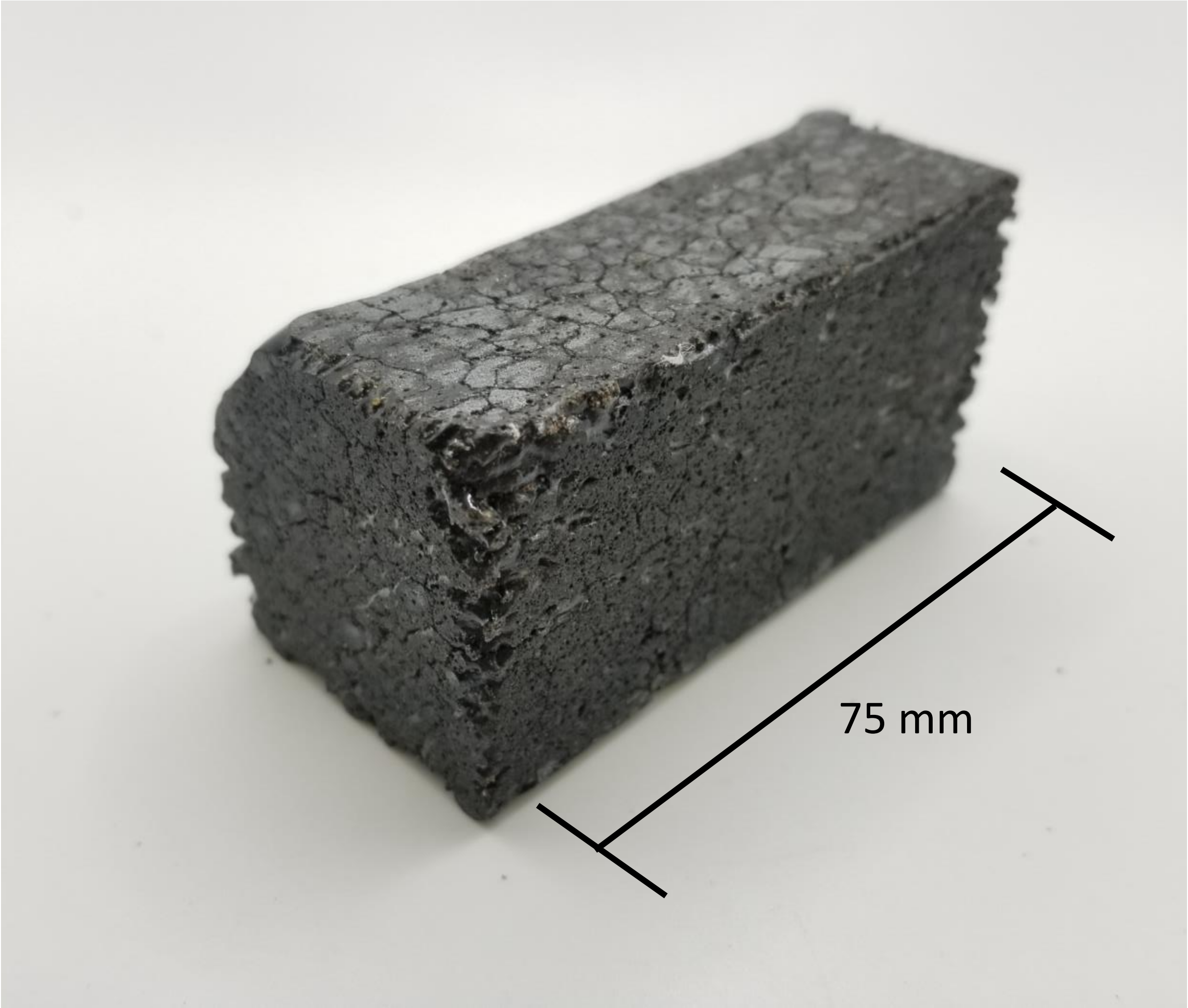
Demonstration Parts – Bricks

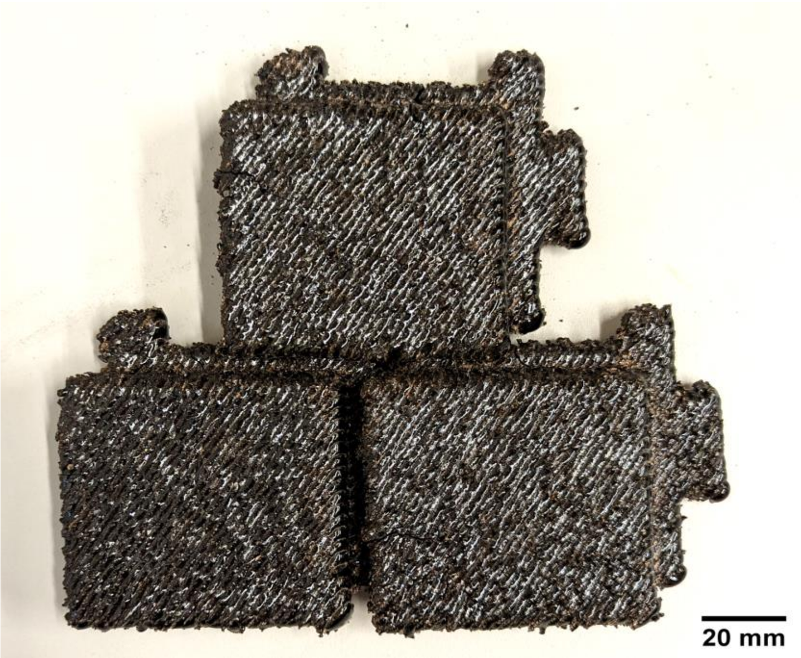




Solid bricks and bricks filled with unmelted regolith

Demonstration Parts – Landing Pads/Pavers

Landing pad load bearing test –
8.7 MPa flexural stress at failure

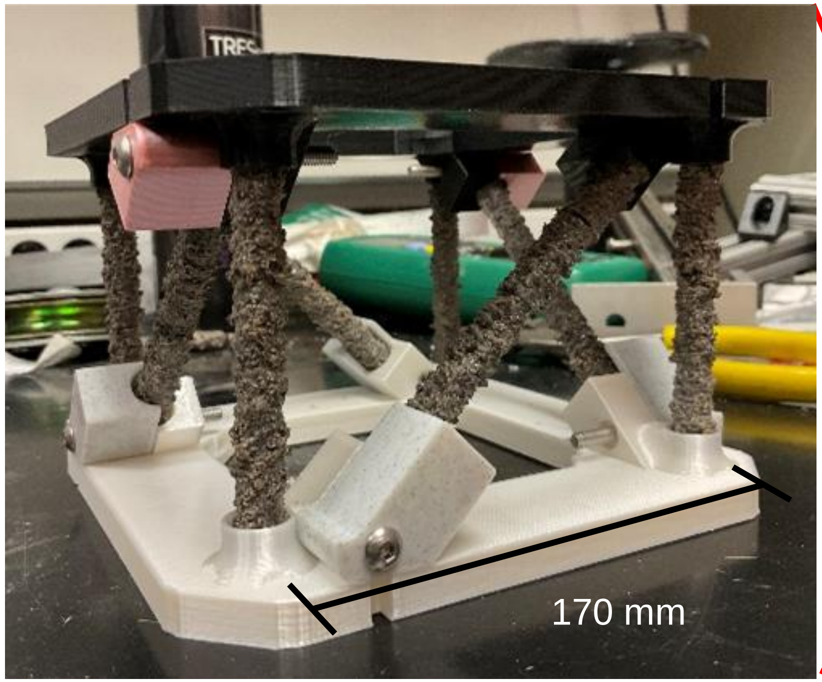


Interlocking landing pad tiles

Overlapping landing pad tiles

Demonstration Parts –Rods, Connectors, and Trusses

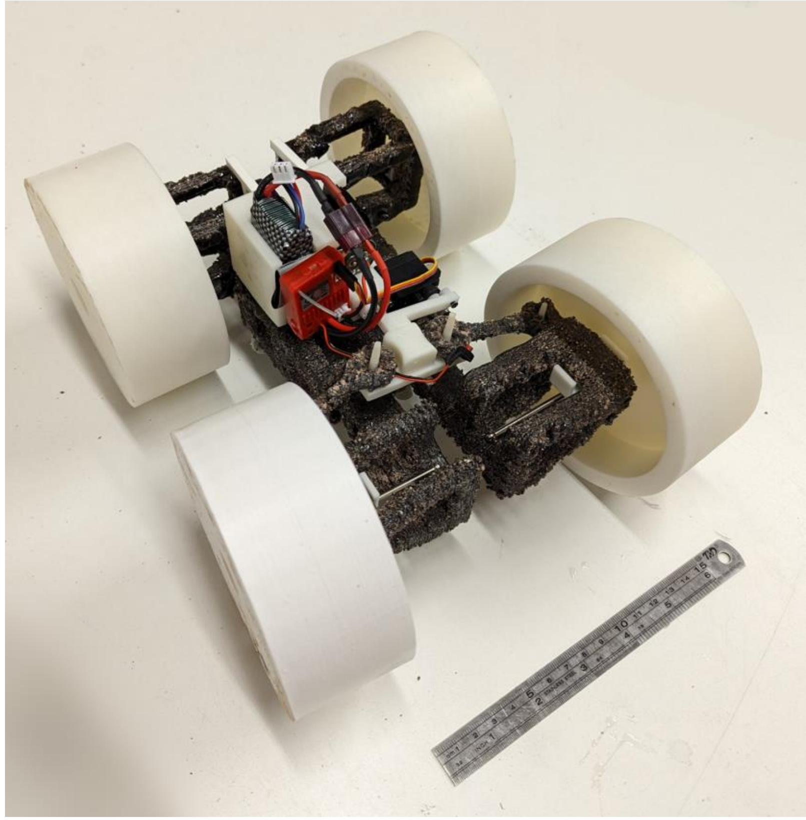
Rod and connector



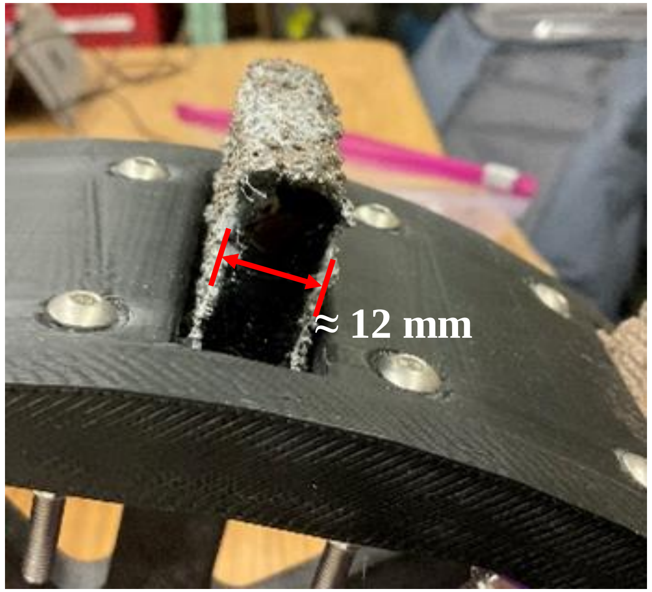
Truss assembly tested at CSM

Truss assembly loaded with 34 kg before failure

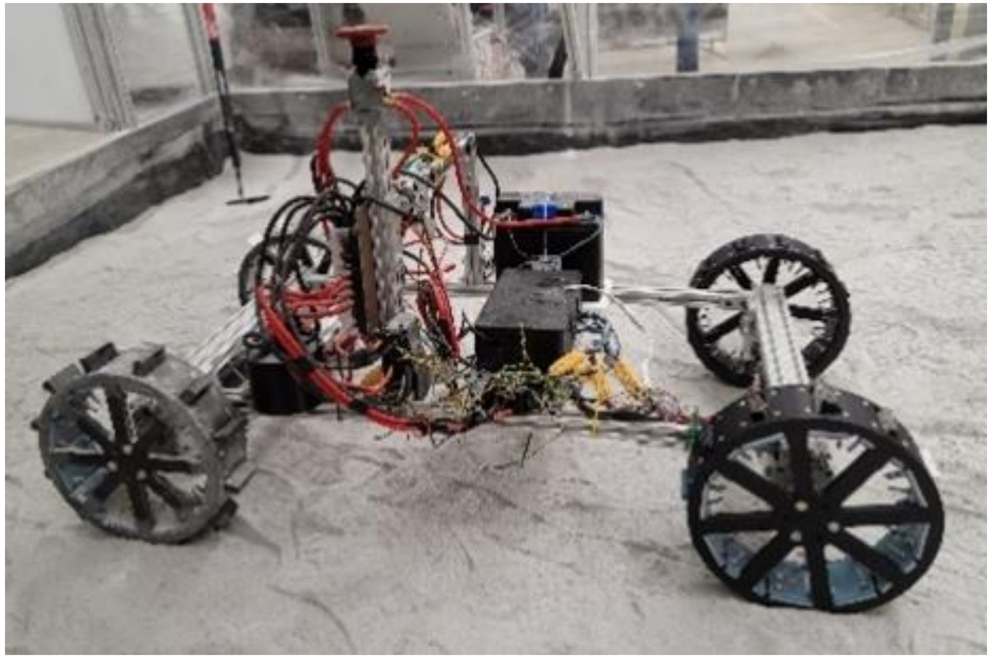
Demonstration Parts – Rover Components



Chassis and steering components



Replaceable grouser being tested

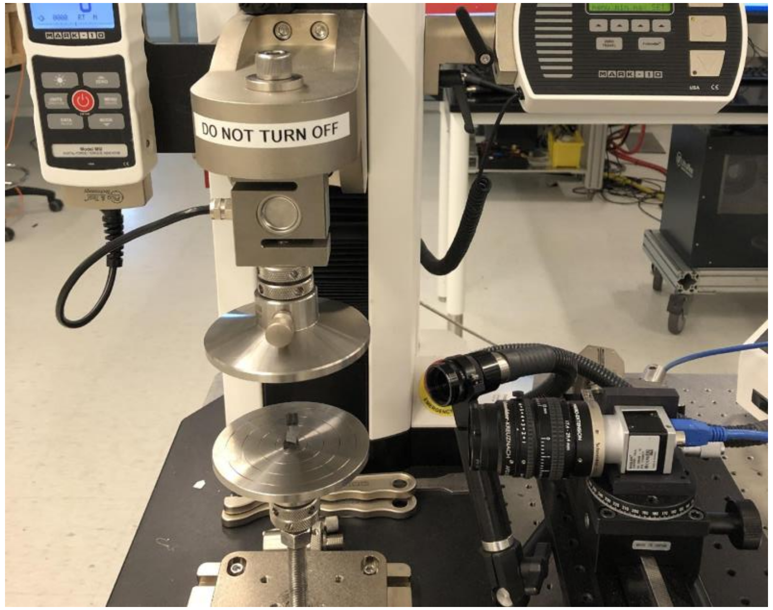


CSM grouser testing

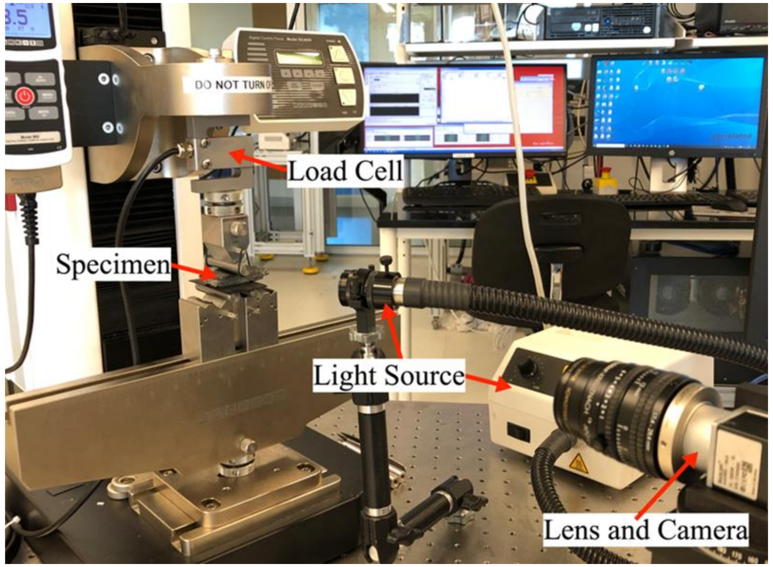
Mechanical Testing

- Two Tests conducted at CSM
  - Compression
    - Compressive strength
    - Young's modulus
  - Bending
    - Flexural strength
    - Flexural modulus
- All Specimen produced with CSM-LHT-1 simulant
- Compliant interfaces used to limit stress concentration
- Displacement measured using digital image correlation

Compression Test Setup



Bending Test Setup



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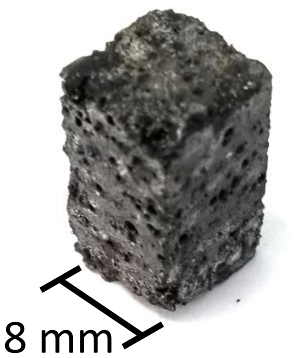
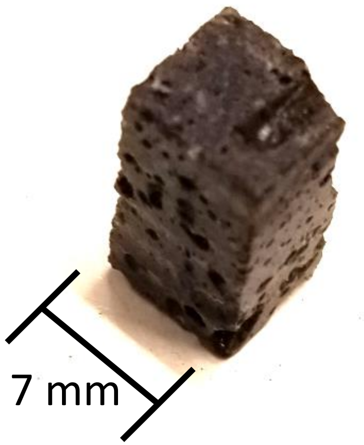
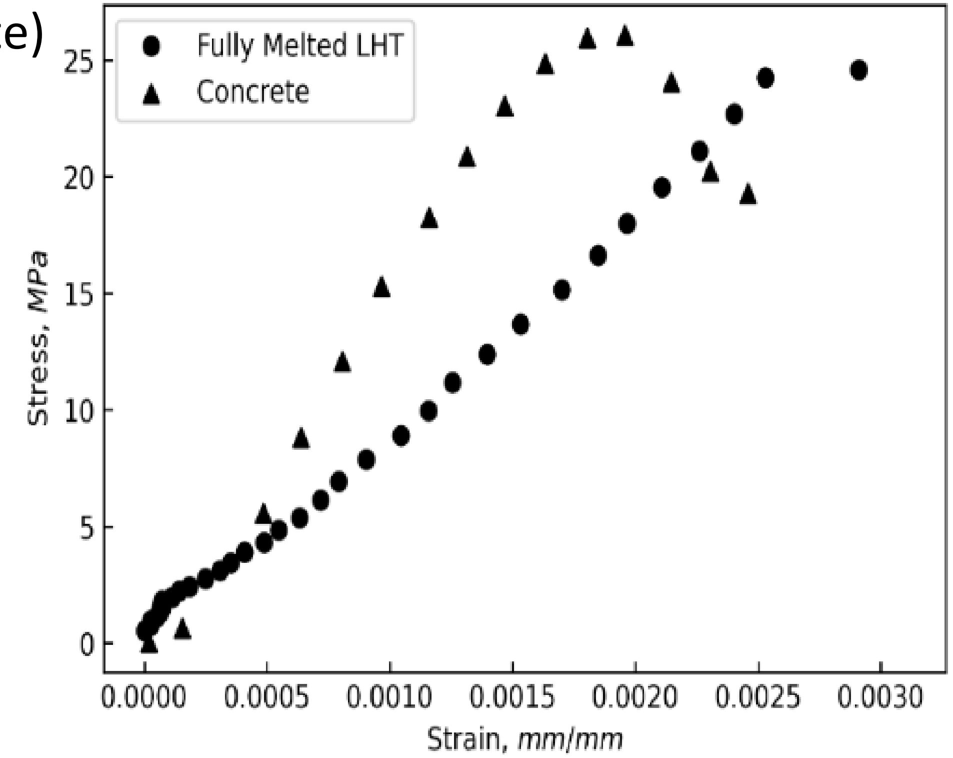
Mechanical Properties – Compression

- PBF
  - Compressive strength: 25 MPa (comparable to M25 Concrete)
  - Young's modulus: 10.3 GPa
- FDM
  - Compressive strength: 36.3 MPa
  - Young's modulus: 13.9 GPa



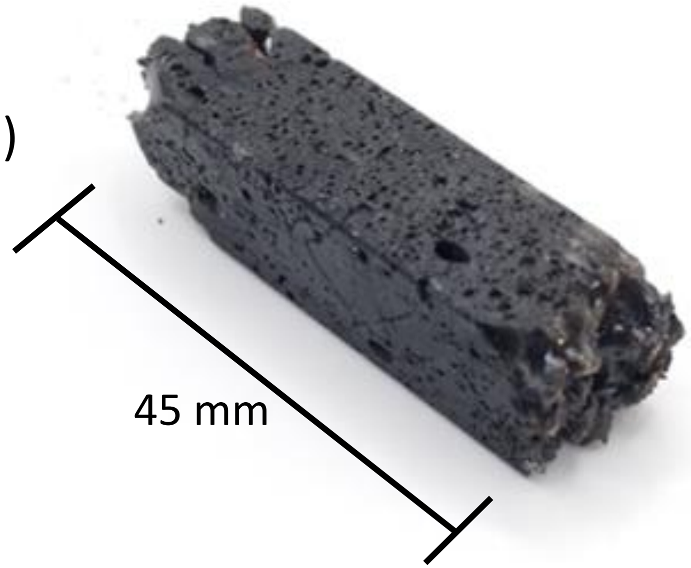




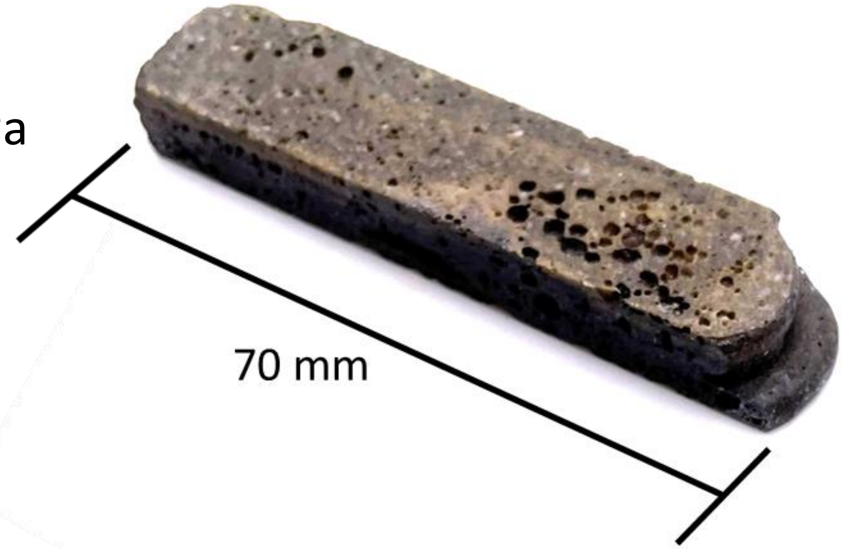
Stress-strain curves for concrete and SAM PBF produced specimen

Mechanical Properties – Bending

- PBF
  - Flexural strength: 3.5 MPa (comparable to M25 Concrete)
  - Flexural modulus: 3.92 GPa



- FDM
  - Flexural strength: 30.1 MPa



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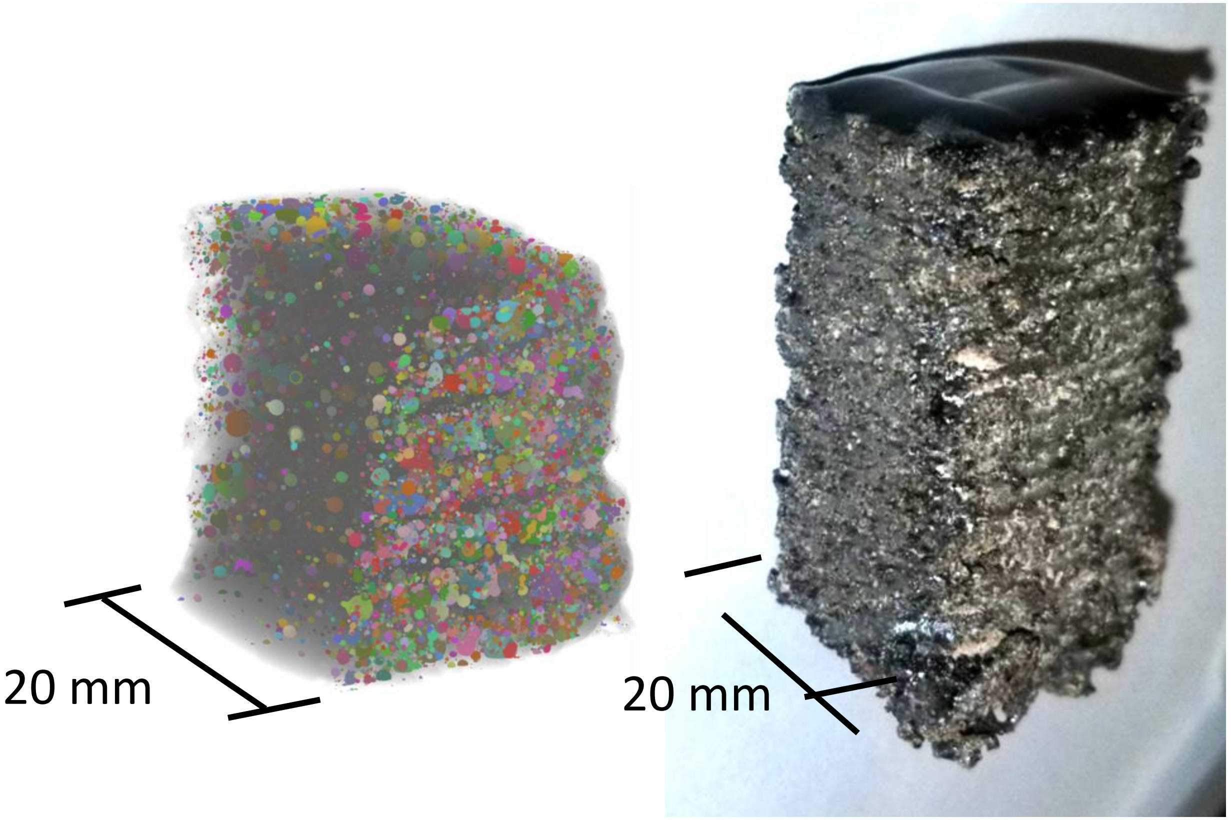
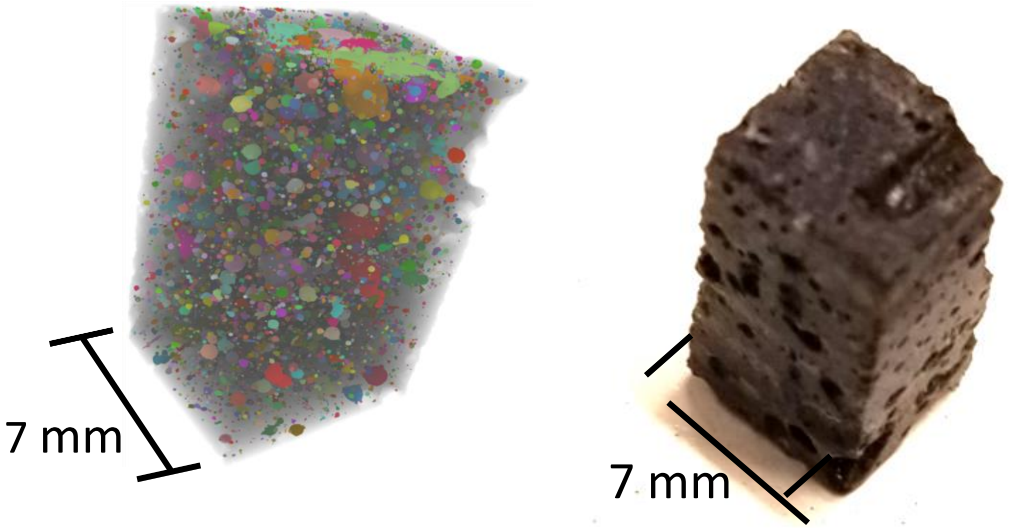
Material Characterization – X-Ray Computed Tomography

- Pores indicated by random coloring
- PBF and FDM produce parts with similar density



PBF: 95% density



FDM: 94.6% density

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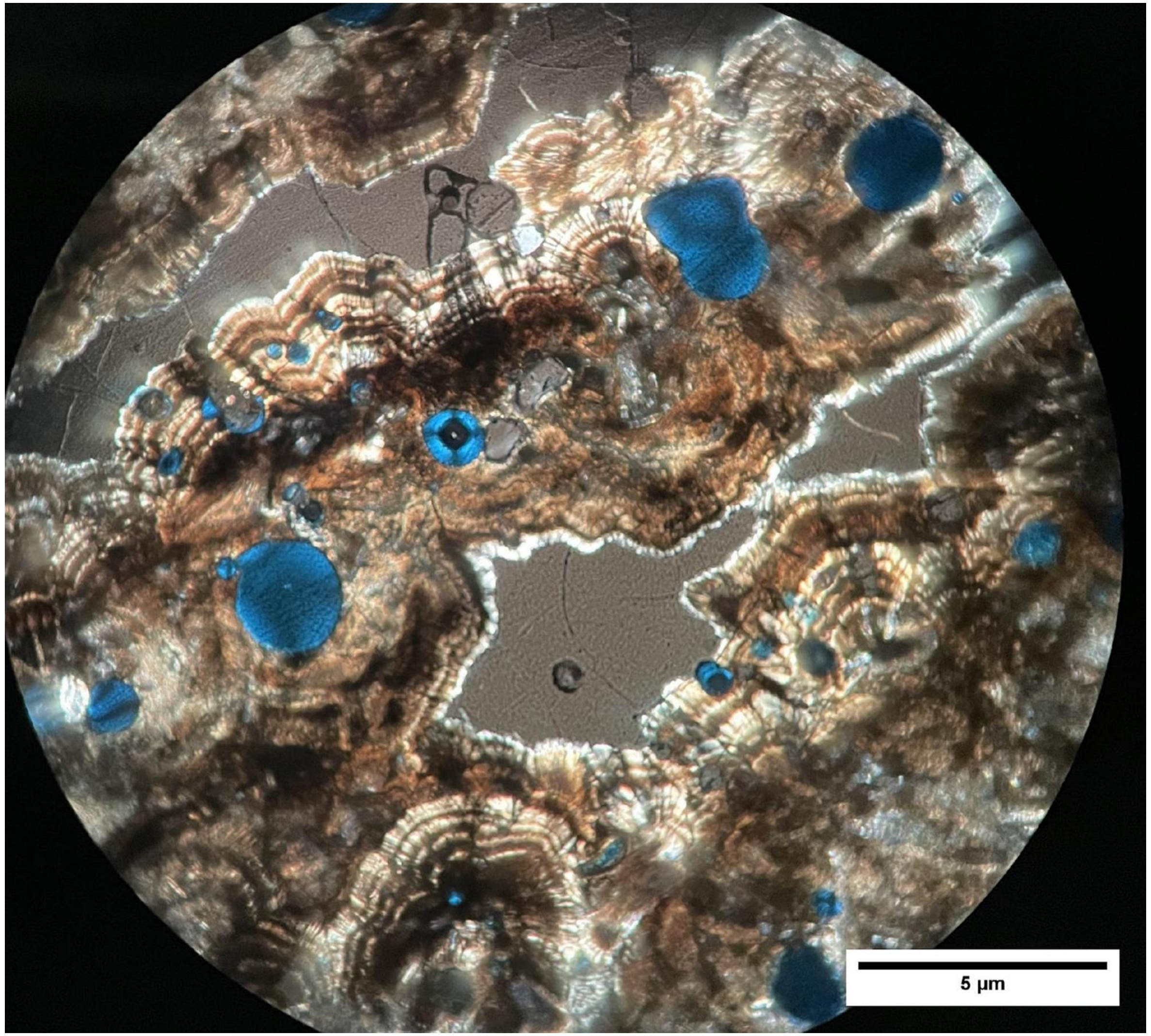
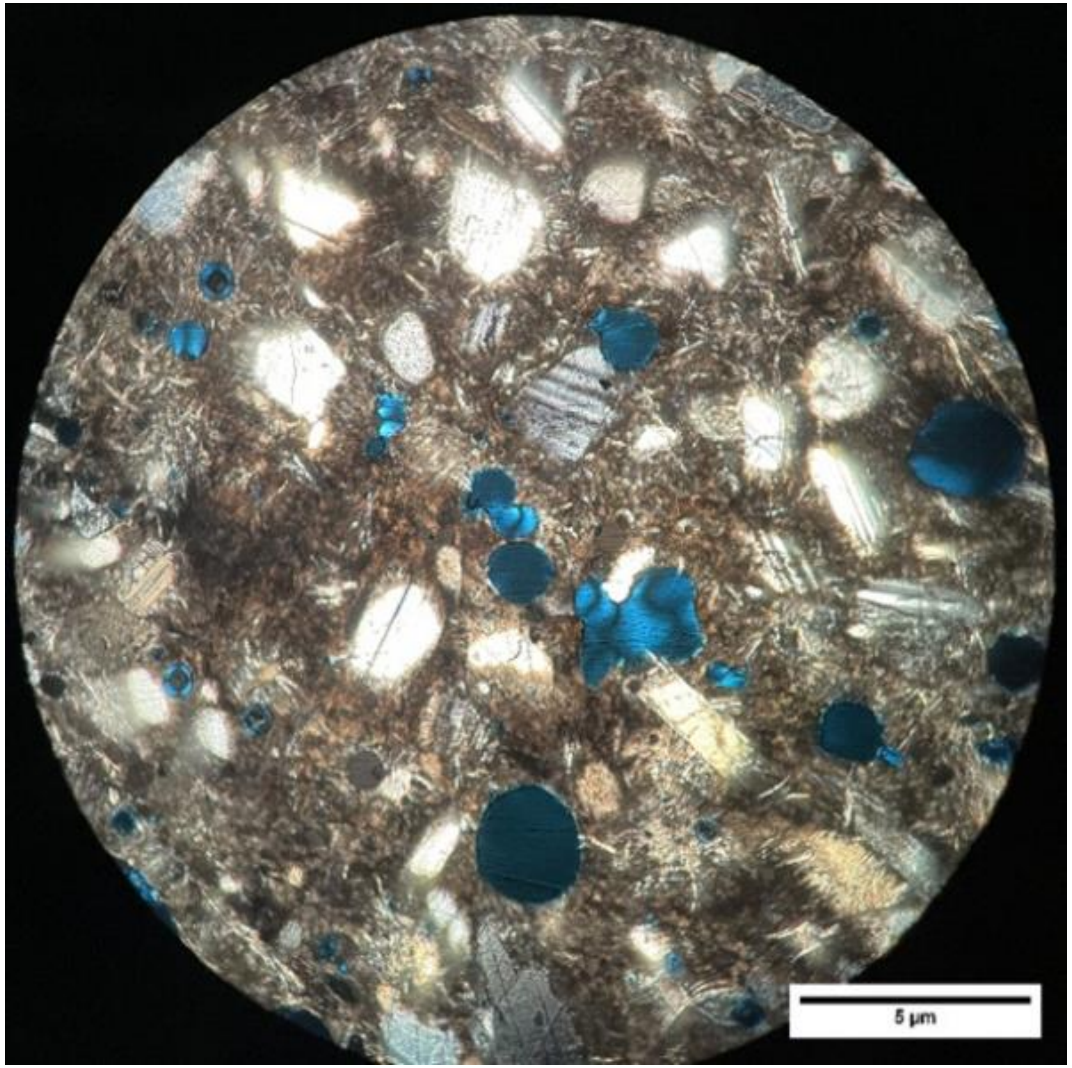
Material Characterization – Thin Sections



PBF specimen, glassy phase present



FDM specimen, no glassy phase present

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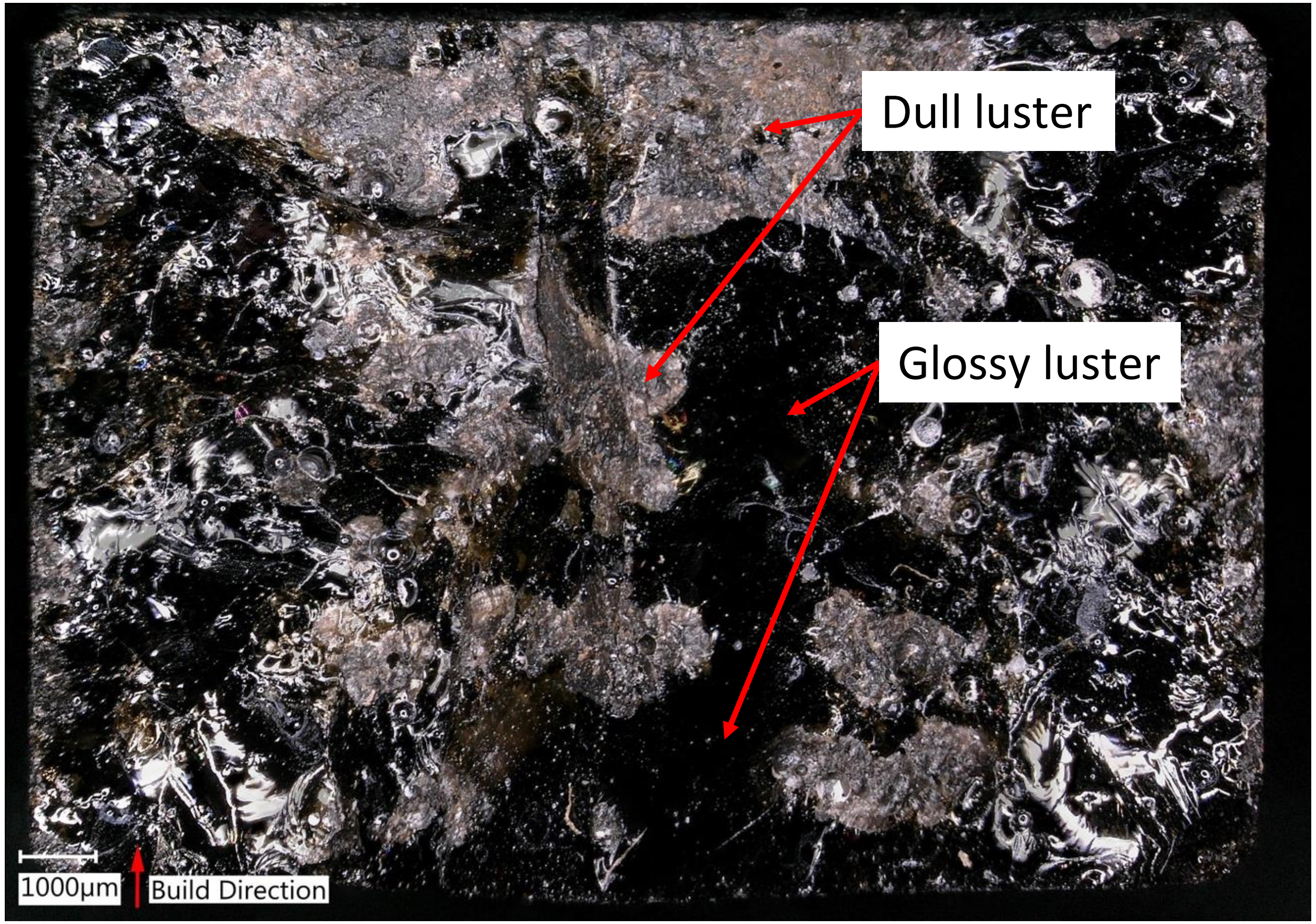
Material Characterization – Fractography



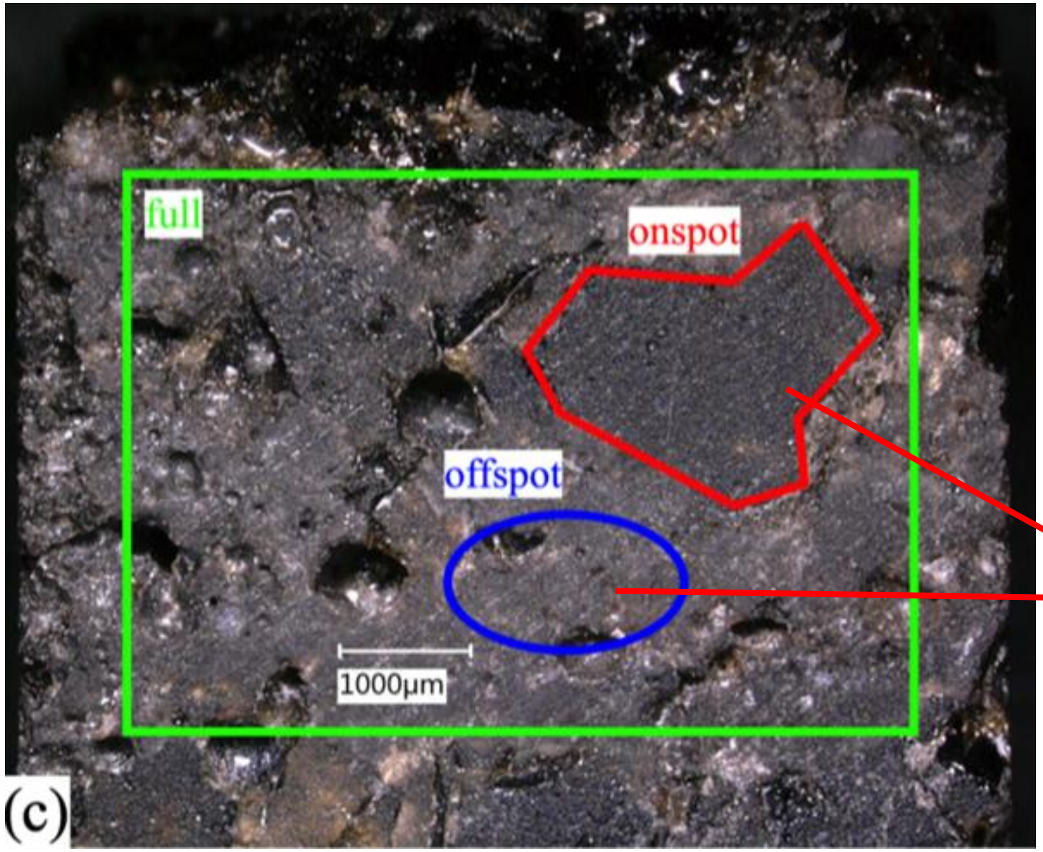
Fracture surface of PBF specimen with flexural strength of 0.6 MPa

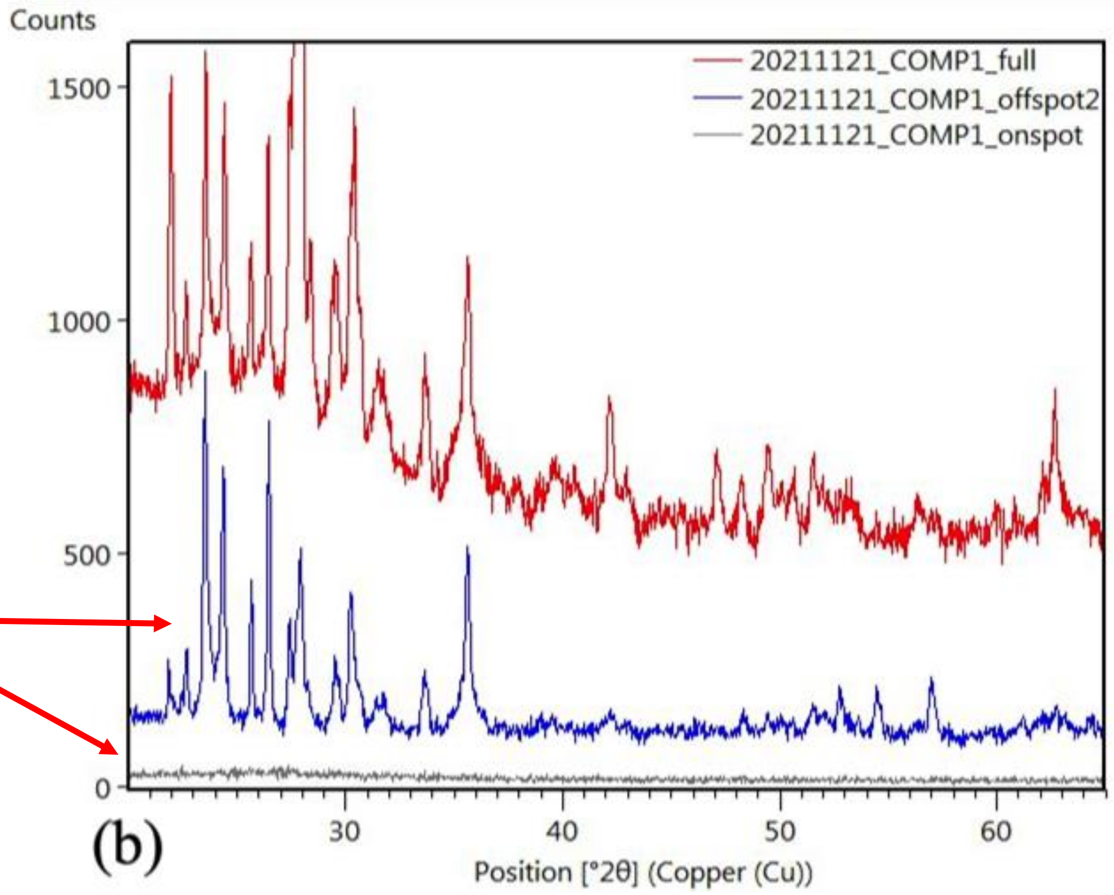
Two fracture behaviors seen in initial PBF bending specimens

- Conchoidal fracture with glossy luster
- Earthy or uneven fracture with dull luster

Material Characterization – X-Ray Diffraction

- Presence of diffraction peaks indicate presence of crystalline material
- Lack of diffraction peaks indicate amorphous material





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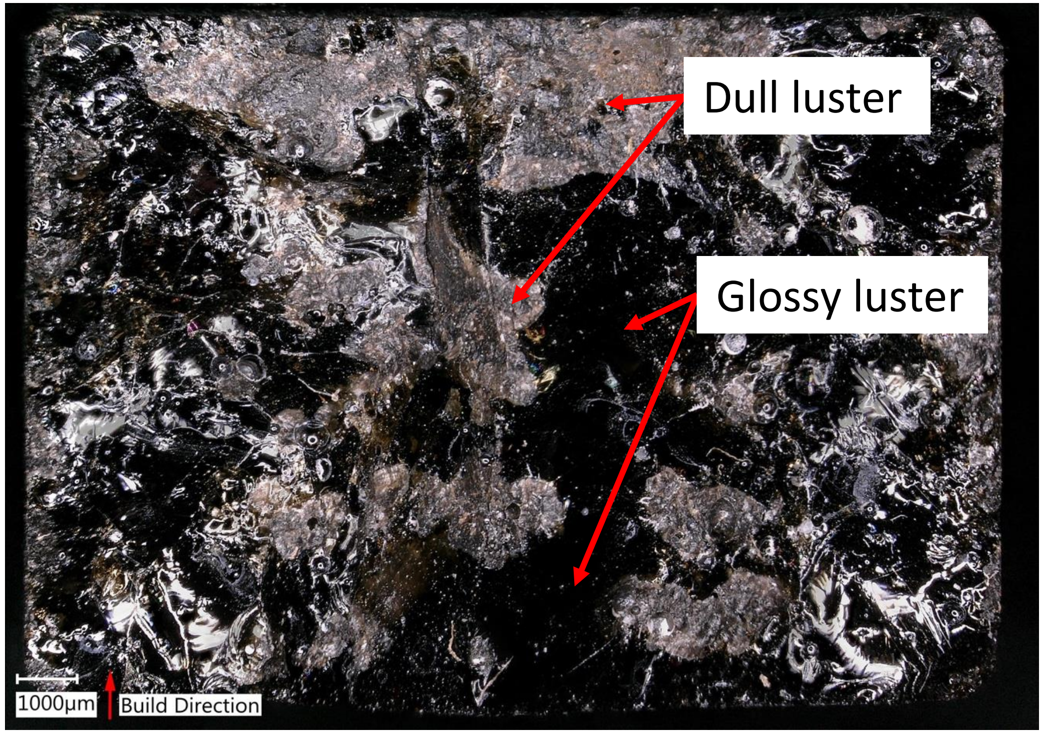
Material Optimization – Fractography

Able to optimize microstructure of PBF specimen using proprietary process parameters

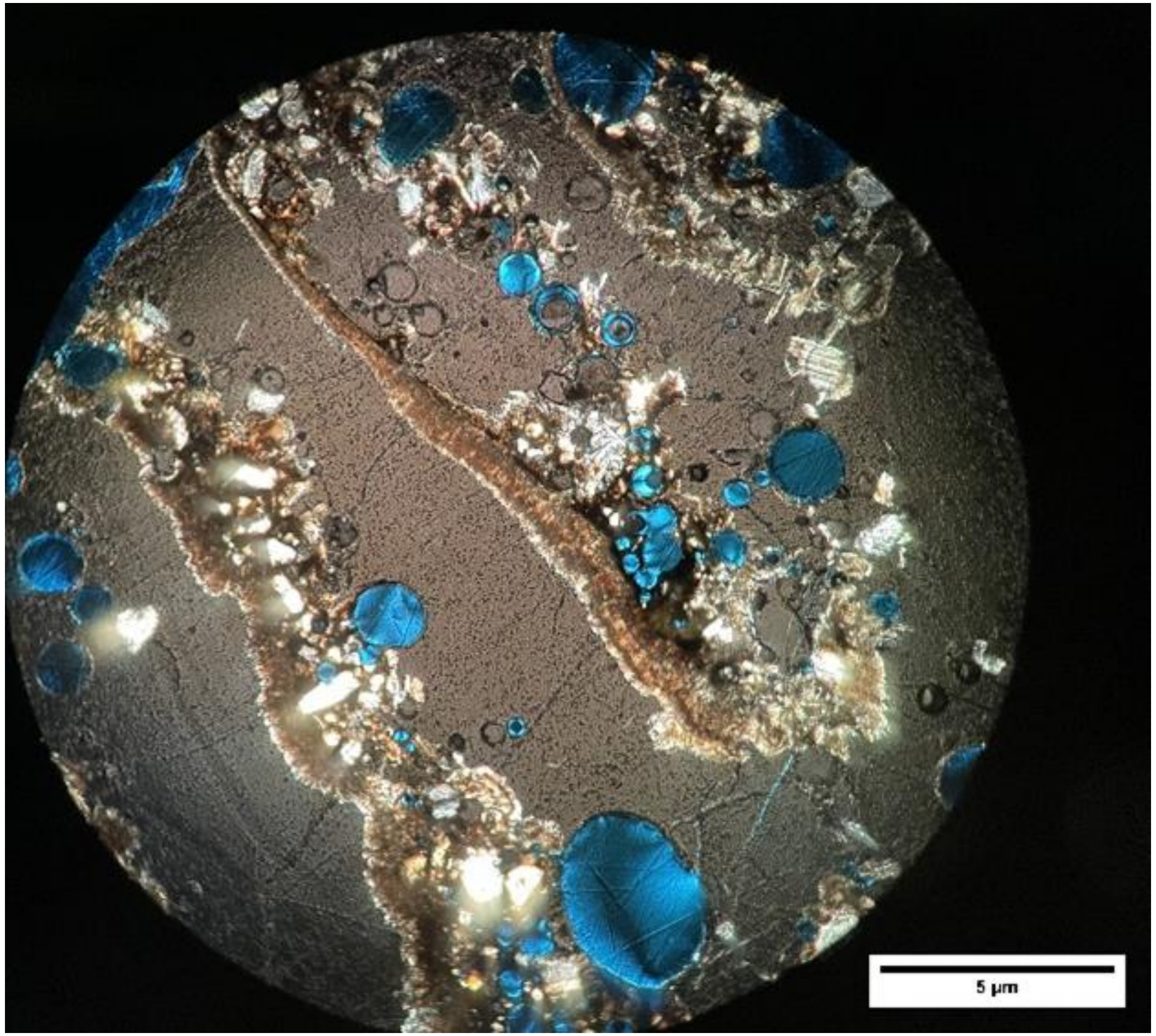
- Minimize glassy phase
- Increased tensile strength



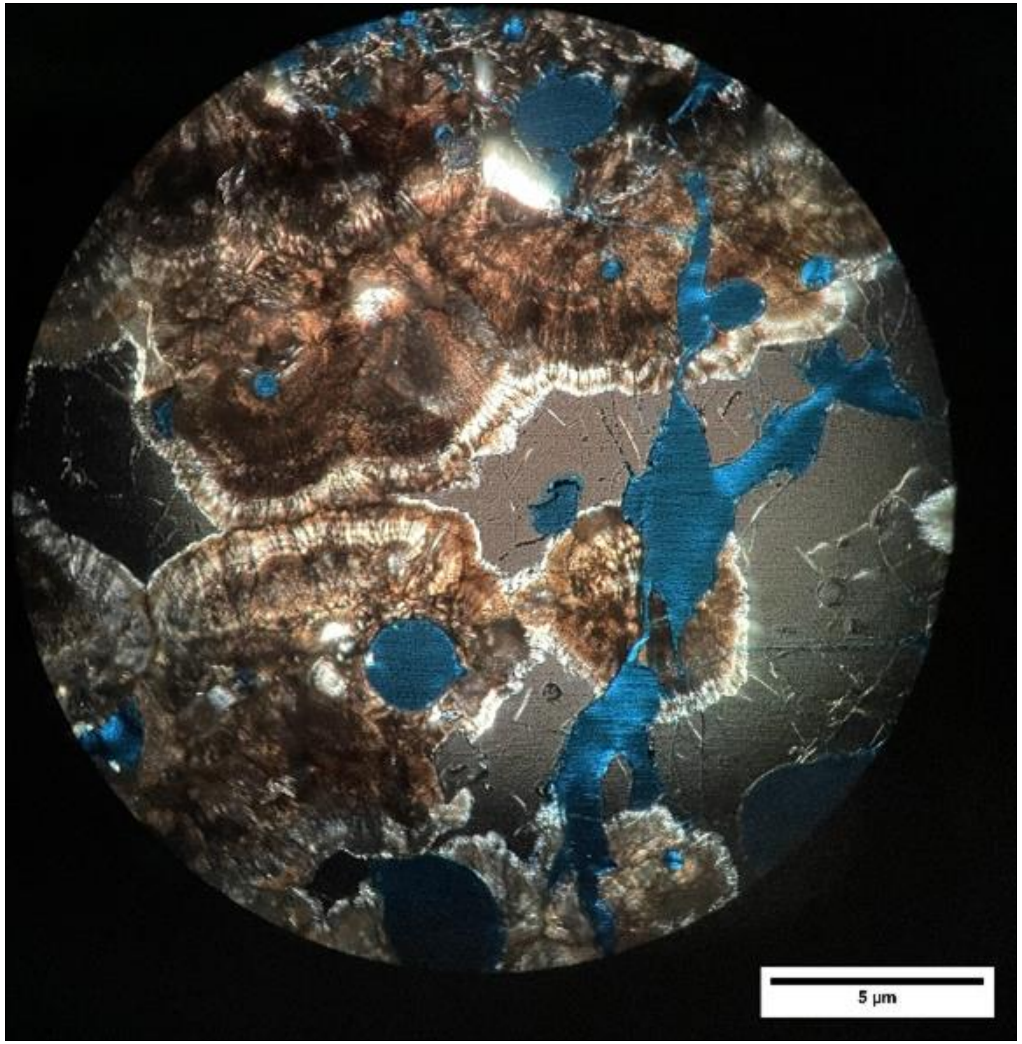
Fracture surface of specimen with flexural strength of 0.6 MPa

Fracture surface of specimen with flexural strength of 4 MPa

Material Optimization – Thin Sections



Weak PBF specimen, majority glassy phase



Stronger PBF specimen, more ground mass and crystallized material

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SAM Architecture – Opportunities for Partnership

Resource Needs:

Regolith

Regolith Beneficiation (minimal to none)

Electrical Power for Mechanical Actuation

Product Needs:

Part Removal

Part Post Processing

Part Storage

Part Delivery

Part Installation

Operational Needs:

Lander Service

Printer Servicing

Printer Repair & Troubleshooting (Human)

OUTWARD TECHNOLOGIES

Questions?

Principal Investigator – Andrew Brewer, abrewer@outward.tech

Project Manager – Ryan Garvey, rgarvey@outward.tech

Additive Manufacturing Engineer – Alan Carter, acarter@outward.tech

Composition of CSM-LHT-1

Oxide	Wt.%
SiO_2	48.0
TiO_2	2.94
Al_2O_3	22.9
FeO	5.7
MgO	1.89
CaO	15.9
Na_2O	2.56

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