SOLAR ADDITIVE MANUFACTURING WITH LUNAR REGOLITH. A. Carter[1], A.T. Brewer[2], and T. Southard[3]; Outward Technologies, 575 Burbank Street, Broomfield, CO 80020, 303-953-0297, outward.tech; [1]acarter@outward.tech, [2]abrewer@outward.tech, [3]tsouthard@outward.tech.

Introduction: A permanent human and robotic presence on the Moon will require substantial infrastructure development, numerous consumables, and will encounter many unforeseen challenges. Outward Technologies is developing a solar powered additive manufacturing platform through an NSF SBIR Phase II project which addresses these issues. Outward's Solar Additive Manufacturing (SAM) platform uses concentrated solar energy to produce mechanical and structural components using regolith feedstock without the need for binders or additives. Two manufacturing methods have been developed by Outward: powder bed fusion (PBF) and fused deposition modeling (FDM). The technology has been shown to produce mechanical components such as grousers for rover wheels (Figure 1) and structural components such as truss assemblies (Figure 2) to produce ramps, bridges, and towers.

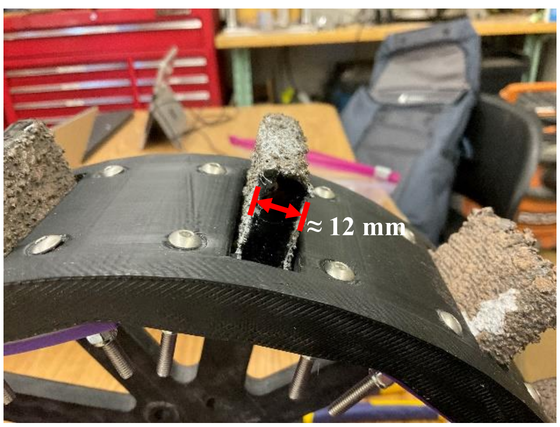


Figure 1: Solar PBF regolith grouser inserted into a rover wheel for testing.

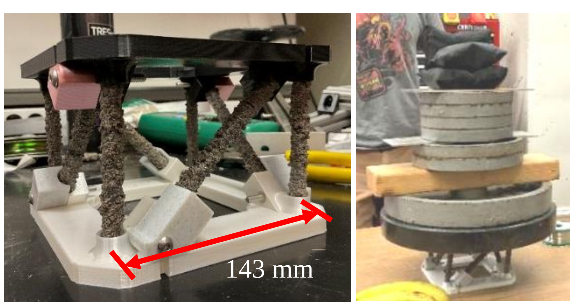


Figure 2: Regolith truss assembly (a) unloaded and (b) loaded with 34 kg.

Deployed on the Moon, Outward's SAM system will drastically reduce launch costs, design constraints, and risk for future lunar missions. First, the SAM platform enables mass production of mechanical and structural components on the lunar surface, reducing the amount of mass that must be launched from Earth for infrastructure development missions. Second, parts produced on the Moon will not be subject to launch vehicle design constraints (G-loading, vibration, mass/volume limitations, and deployability requirements), enabling greater design flexibility. Third, SAM enables component designs to be modified and iterated post-deployment, further increasing design flexibility and mitigating unforeseen mission challenges.

Through process characterization and optimization, mechanical testing has shown the fused regolith specimens produced by SAM PBF have compressive and flexural strength properties equivalent to grade M25. FDM produced specimens have even higher compressive and flexural strength. Additionally, microstructural characterization of SAM produced specimens shows the presence of glassy amorphous and rocky crystalline microstructures which can be linked to the mechanical behavior of the fused regolith parts.

Mechanical Properties of SAM Parts: Compression and bending tests were performed on SAM PBF and FDM produced specimens for process development, characterization, and optimization. All specimens were produced from CSM-LHT-1 lunar highlands regolith simulant. Testing standards ASTM C1161-18 and C1424-15 were followed for the compression and bending tests with the exception of specimen geometry.

Following process optimization, eight compression tests were conducted on SAM PBF specimens, resulting in a compressive strength of 25 MPa and a Young's modulus of 8.18 GPa. Figure 3 presents the stress-strain curve for a typical SAM PBF specimen compared to the stress-strain curve for grade M25 concrete [3]. Not only does the fused regolith have comparable compressive strength, it has 20% more strain at failure and higher toughness than grade M25 concrete. The Young's modulus of the PBF specimens is about half of grade M25 concrete which is still sufficient for some mechanical and structural applications. The flexural strength measured for SAM PBF printed specimens was 3.5 MPa. These properties demonstrate that the SAM PBF process can be used for large-scale manufacturing to replace concrete-type infrastructure on the Moon (landing pads, roads, habitats/enclosures). These properties can also be leveraged for large truss structures (towers) using regolith truss elements as long as the truss system is designed to minimize tensile loads on the truss elements.

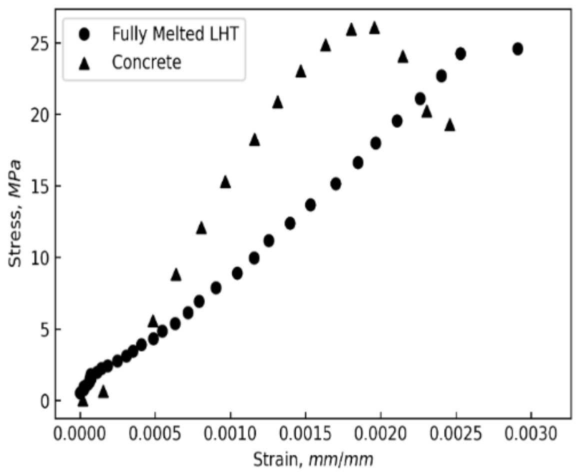


Figure 3: Stress strain curves comparing compressive strength of fully melted LHT specimens with that of concrete [1]**.**

A single regolith FDM specimen was also tested in compression and bending, resulting in significantly higher compressive strength (36 MPa) and flexural strength (30.1 MPa), which can be leveraged for producing high strength mechanical components at a smaller scale than the SAM PBF process.

Microstructure of SAM Fused Regolith: Two microstructures were observed during testing as seen in Figure 4. One had a dull/matt luster, contained spherical porosity, was observed around the outer edges of the specimens, and exhibited XRD diffraction peaks indicating crystallinity. The other was observed within the center of most specimens, had a glossy luster, exhibited no internal porosity, and lacked any XRD diffraction peaks indicating it was an amorphous phase. Both microstructures were usually present in a fused part across wide ranges of process parameters.

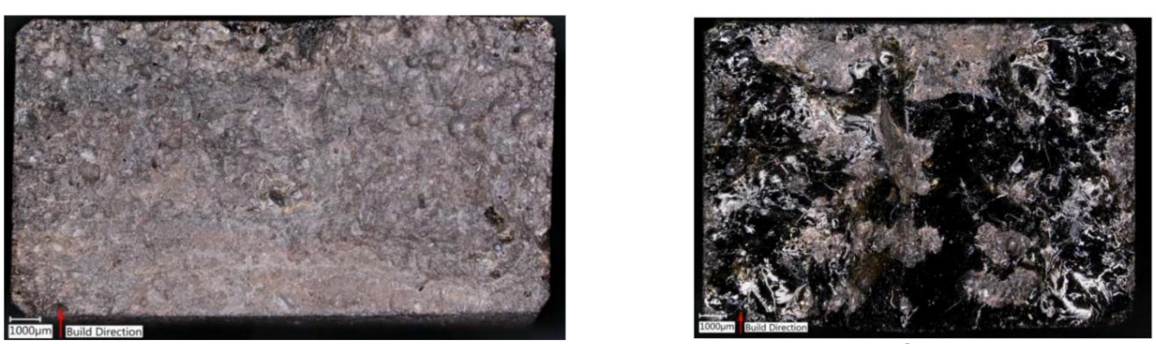
The specimen microstructure led to differences in machinability and strength. Specimens exhibiting more matt microstructure were more machinable than the glossier microstructure. However, Outward has identified a simple post-processing method that enables precision component interfaces to within +/- 0.1 mm for both microstructures. Also, specimens with more matt microstructure exhibited higher flexural strength (1.75x) and Young's modulus (2.4x) than the glossy microstructure due to fewer internal defects and a large volume of the matt material carrying more load.

Conclusion: Outward Technologies' SAM system will be able to produce complex parts and structures on the Moon using concentrated solar energy as the heat source and regolith as the feedstock without binders or additives. The SAM system requires minimal electrical power and minimal beneficiation of the regolith prior to its use in the manufacturing process.

SAM PBF parts have strengths equivalent to grade M25 concrete that, with custom designs to accommodate these mechanical properties, can be used for large scale lunar infrastructure development missions. Parts required in mass quantities, like structural truss elements, can be made from regolith on the Moon, thereby significantly reducing the amount of mass that must be sent from Earth and the number of deliveries that would be required to produce large structures, like a 50 m tall solar tower.

Outward's regolith FDM produces high strength parts, however the process is complex making it more suited for the manufacture of smaller scale mechanical components. Outward's regolith PBF produces lower strength parts, but the technology is simple and scalable, making it most applicable to the manufacture of large structures such as habitats and towers. Through continued advancement of these methods, near limitless quantities of parts and structures may be produced on the Moon from lunar regolith heated and fused by concentrated solar energy.

References: [1] F. Bousikhane, R. Rezakhani, G. Di Luzio, J. Smith, and G. Cusatis, "Numerical Simulation of Quasi-Static and Dynamic Experiments of Standard and Dam Concrete," 2016, doi: 10.21012/fc9.284.



(a) (b)

Figure 4: Micrographs of bending specimen fracture surfaces showing (a) crystalline material with a dull/matt luster and (b) glossy amorphous material with some matt crystalline material.