



HAL
open science

Additive manufacturing on the Moon with Selective Laser Melting: mechanical properties and microstructure of printed small objects

Julien Granier, Thierry Cutard, Patrick C. Pinet, Yannick Le Maout, Thierry Sentenac, Serge D. Chevrel

► To cite this version:

Julien Granier, Thierry Cutard, Patrick C. Pinet, Yannick Le Maout, Thierry Sentenac, et al.. Additive manufacturing on the Moon with Selective Laser Melting: mechanical properties and microstructure of printed small objects. European Lunar Symposium (ELS) 12th, Jun 2024, Dumfries, United Kingdom. pp.195-196. hal-04791828

HAL Id: hal-04791828

<https://hal.science/hal-04791828v1>

Submitted on 19 Nov 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Additive manufacturing on the Moon with Selective Laser Melting: mechanical properties and microstructure of printed small objects

J. Granier^{1,2} (julien.granier@mines-albi.fr), T. Cutard¹, P. Pinet², Y. Le Maoult¹, Thierry Sentenac¹, S. Chevrel². ¹Institut Clément Ader (ICA); Université de Toulouse; CNRS, IMT Mines Albi, INSA, ISAE-SUPAERO, UPS; Campus Jarlard, F-81013 Albi, France, ²Institut de Recherche en Astrophysique et Planétologie (IRAP), CNRS/CNES, Observatoire Midi-Pyrénées, Université de Toulouse, France.

Introduction: The next Artemis missions are fast approaching and are to contribute to the establishment of a permanent lunar base, leaving room for ISRU technologies development.

One of those technologies, Selective Laser Melting (SLM), has been explored in the last few years mainly as a way to make large structures like habitats, or more recently paved roads [1], all derived from the lunar regolith. Preliminary work on the effect of the lunar environment considering vacuum and microgravity [2] shows a clear intent to use SLM in outdoor situations, using a rover as developed in the MOONRISE project.

However, SLM also has a significant potential in manufacturing complex objects from a few millimeters to tens of centimeters. This presentation aims to highlight a few valuable mechanical and surface properties that can be reached.

As a base material for additive manufacturing experiments, and as shown during 2022 and 2023 ELS editions [3], the BPY (Basalt of Pic d'Ysson), an analog produced from an unweathered basaltic lava flow in the French Massif Central is used. BPY is a mare analog with a tunable content ratio, which has a documented impact on melting, sintering, and solidification phenomena, as partially illustrated by Fig.1.

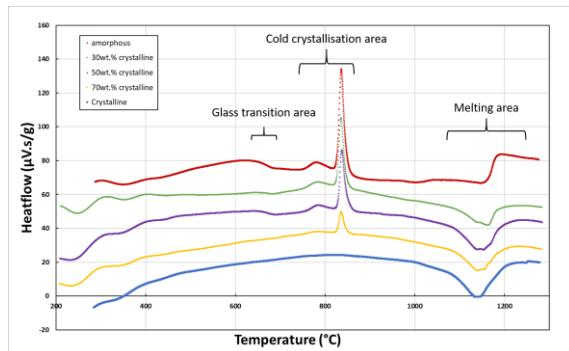


Fig 1: DTA curves of various crystalline and amorphous powder mixtures of BPY analog (wt.%), during first heating. To facilitate the readability of the graph, the curves have been translated vertically to avoid overlapping

Additive manufacturing experiments: Every trial presented here has been prepared with an SLM125HL from SLM Solutions, using an Nd-YAG laser under an argon atmosphere. Main experimental parameters can be directly established from the Volumetric Energy Density (VED) provided by the laser, and described by the simplified following equation:

$$VED = \frac{P}{v \cdot e \cdot h}$$

With P the laser power (34-56W), v the laser scanning speed (150-250mm/s), e the powder layer thickness (200-300µm), and h the laser hatching distance (55µm, with a laser spot size of 60µm).

Several shapes have been tested, from nuts to cubic structures, but 3 objects have been intensively replicated: 26mm long, 2,5mm wide, and 10mm tall parallelepipeds, and 10mm tall cylinders of respectively 3 and 6mm in diameter, all shown in Fig.2.

Despite a pre-heating of the working substrate at 200°C, the extreme thermal gradients in the material sometimes lead to a local disbanding of the base of the longest objects. This phenomenon is already mentioned in the literature as the wrapping effect [4].

Other defects are commonly found in the samples, such as cracks, porosities from lack of fusion and/or powder vaporization, and residual crystalline phases. A relationship between the additive manufacturing strategy (chosen substrate material, energy density, sample extraction method), the presence or not of those defects, and resulting mechanical strength have been investigated as mentioned in the next section.

Mechanical properties: 3mm diameter cylinders have been selected for uniaxial compressive tests because of their easy production and their reduced variability in size and defect occurrence compared to the other specimens. An Instron 5967 30kN electromechanical testing machine has been used, with an imposed crosshead displacement of 0.025mm/s. The complexity involved in the production of manufactured regolith-based objects is addressed in Fig.2 with their non-linear multi-cracking mechanical behavior in compression, which is not dependent on the maximal strength exhibited by the sample. It is important to note that for general use, and as a ceramic material, BPY-based SLM samples already exhibit quite a satisfying compressive resistance on average compared to usual materials (compressive resistance of 40MPa for concrete for example). Correlation with Young's modulus and porosity ratio is also discussed.

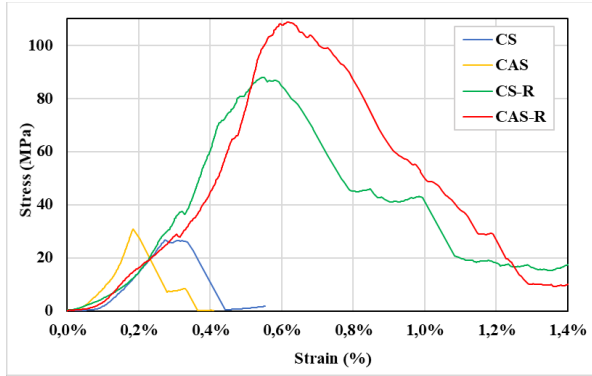


Fig 2: Typical compressive stress-strain curves for samples made with 100% crystalline BPY (CS), a mix of 50% crystalline-50% amorphous content (CAS), and on both categories subjected to an annealing step (CS-R, CAS-R)

These mechanical properties are linked to the variety of microstructures of the printed objects, as demonstrated in this presentation through electron microscope observation and micro indentation tests.

Among other things, the extreme cooling kinetics imposed by laser fusion creates predominantly amorphous structures, which are very sensitive to the presence of anomalies and thermal treatments. Residual crystalline phases play an ambiguous role, mostly deflecting cracks, but in certain cases and depending on their nature can also contribute to crack propagation. Annealing processes, on another hand, contribute to mitigate residual stresses in the glass and form a more mechanically resistant crystalline phase, as shown in Fig.3.

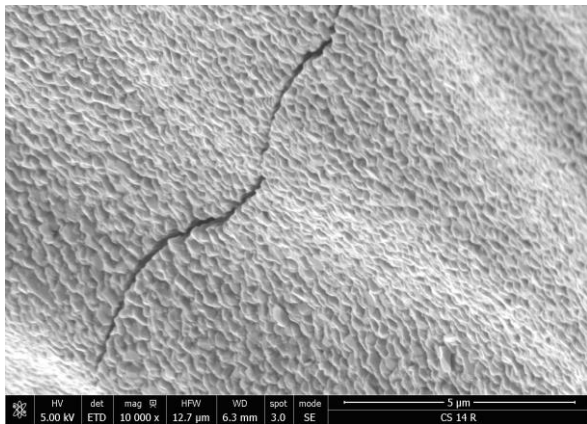


Fig 3: Intergranular crack propagation in a recrystallized matrix, made by the annealing of an additive manufacturing sample

Perspectives: At this stage, our Selective Laser Melting outputs lead to products with a minimal feature size (Fig.4) mainly limited by the size of the powder grains (that tend to be linked to the surface of the object without necessarily completely melting), but with enough mechanical resistance to start considering useful applications. Lattice structure and gyroid shapes are being considered as candidates to form efficient heat exchangers and particle filters. The effect of the diversity of the lunar mare regolith is to be considered very soon by doping the Ti-poor BPY with ilmenite.

More prospectively the additive manufacturing of cermet structures using both regolith and metallic powders (which can be also a product of ISRU technologies with the electrolysis of a variety of elements like aluminum, iron, magnesium, titanium...) could also be a solution to give more ductility and toughness to the final product without degrading its hardness.

A more complex aspect would be the delivery of samples to address toughness and flexural strength tests. These experiments are required to fully comprehend ceramic materials' overall mechanical resistance. It would be then required to have a more precise control of wrapping effect and porosity. This can be investigated by the addition of numerical modeling of the SLM process using Finite Element Method, based on the thermal and optical properties of BPY as a function of temperature.



Fig 4: SLM-made bishop and knight chess pieces, both with a 1 cm base diameter

References: [1] Ginés-Palomares J. et al. (2023) *Sci Rep.* **13**, 15593. [2] Reitz, B. et al. (2021) *Microgravity Sci. Technol.* **33**, 25 [3] Granier J. et al. (2023), *ELS 2023- In-Situ Resource Utilization.* [4] Shen T. et al. (2023), *Powder Technology* **425**, 118552.