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Selective laser melting of regolith for optimized small objects manufacturing in a lunar ISRU context

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Introduction: The next Artemis missions are fast approaching, still intending to establish 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 has also a huge potential in the manufacturing of complex objects from a range of 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 in a previous authors' work [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.

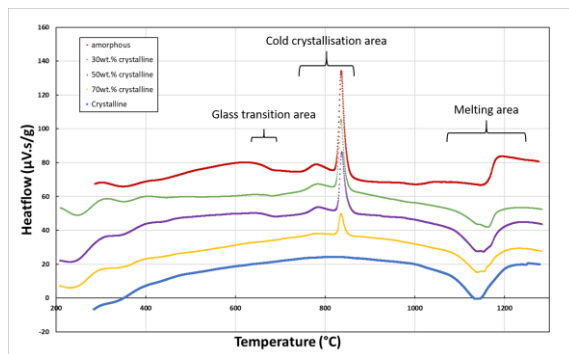


Fig 1: DTA curves of various crystalline and amorphous powder mixtures of BPY analog (wt.%), during first heating. To facilitate the readability of the graph, the curves have been translated vertically to avoid overlapping

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, as shown in Fig.2. 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, thermal post-treatment), the presence or not of those defects, and resulting mechanical strength have already been investigated and will be discussed.

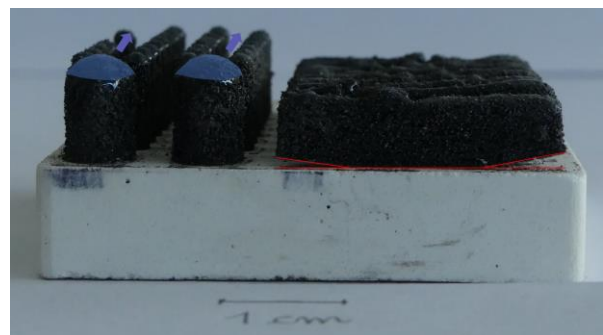


Fig 2: Photograph of SLM samples made with 100% crystalline BPY powder on a vitreous silica substrate. Wrapping (in red) and argon flux effects (blue) are represented.

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.3 with their non-linear multi-cracking mechanical behavior in compression, which is not dependent on the maximal strength exhibited by the sample. Several causes are under investigation, from residual crystalline phases acting as crack deflectors to pre-damage from the sample extraction step. Relationships with Young's modulus, porosity ratio, and phase transformation induced by an annealing step are also discussed, supported with SEM observations. 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).

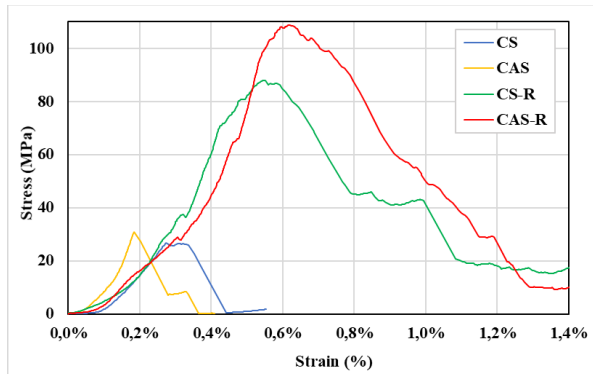


Fig 3: Typical compressive stress-strain curves for samples made with 100% crystalline BPY (CS), a mix of 50% amorphous content (CAS), and both categories but with an annealing step (CS-R, CAS-R)

Perspectives: At this stage, Selective Laser Melting allows a good 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 complete melting), and 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. At the same time, the effect of the diversity of the lunar mare regolith is to be considered 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 production of samples for toughness and flexural strength testes,

which are both crucial to determine for a ceramic material. 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 calculations, based on the thermal and optical properties of BPY in 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.