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CHARACTERIZATION AND PHYSICAL PROPERTIES OF A LUNAR REGOLITH ANALOG FOR POWDER BED FUSION-BASED ADDITIVE MANUFACTURING PROCESSES.

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Introduction: These last years, a renewed interest has emerged from the major space agencies for space exploration, with a particular focus on moon colonization. As a consequence, because of the need for future astronauts to be as self-sufficient as possible and because the cost of a 1 kg delivery on the moon with the American SLS is estimated at \$75000 [1], there is a real need for ISRU¹ based technologies development. Given its flexibility and potential, additive manufacturing is one of the most considered solutions for lunar regolith exploitation, allowing to make objects at different scales, from millimetric tools to parts of habitat shielding walls. Due to insufficient quantities of real regolith samples, a large number of regolith analogs have been designed for a wide variety of uses, often with no relation to manufacturing at all [2]. This presentation will aim to show how the regolith analog used in this project, linked to the activities of the ISRU taskforce in Toulouse [3], is representative of real regolith samples, regarding the behavior expressed under high temperatures, as well as describing the first selective laser melting (SLM) tentatives. The objective is in particular to characterize and to better understand the behavior of a lunar regolith analog during a first thermal cycle. The analog powder is first characterized in order to establish its properties in terms of chemical composition, mineralogy and particle size distribution. These results allow us to know the initial state of the considered material, to situate it in relation to the literature on regoliths and their simulants, and to estimate its ability to be processed with an SLM machine. In this respect, particular emphasis is given to the physicochemical transformations and state changes (glass transition, partial or total melting, crystallization, ...) that can take place during a first thermal cycle. A specific interest is put on the characterization of the thermal and thermo-optical properties of this analog, always as a function of temperature. More generally, this study is part of work aimed at identifying SLM parameters and an SLM process window that are suitable for the manufacturing of parts with controlled performances, using an approach that combines experience and multi-physics modeling. Accordingly, particular attention has been paid to the sensitivity of the process to the variability of the initial properties of the lunar regolith, and thus here of the considered analog.

Chemical composition and Mineralogy of the Ysson analog powder: The upper unconsolidated layer of the moon, called regolith, is mainly composed of a variety of oxides, SiO₂ being the most abundant one. The difference in chemical composition across the surface of the moon is mainly between two types of areas: the anorthositic Highlands (rich in aluminum) and the basaltic Mare, which are the darkest spots visible from Earth and contain significantly more iron and titanium. The lunar analog used in the present work originates from an unweathered lava flow located in the Pic d'Ysson (Massif Central, France). It contains some phenocrysts of olivine, pyroxene, plagioclase and has been mechanically ground and sieved. The largest grains are composite polycrystalline regular blocks with a rough aspect and some visible shiny facets of phenocrysts. This analog has already been used at IRAP for laboratory studies on the lunar regolith optical and spectrophotometric behavior [4]. Its constituents have been determined by microprobe and XRD analysis and match at first order the overall mineralogy of real regolith: each main mineralogical constituent has been detected, in particular anorthite (plagioclases), diopside (pyroxenes), forsterite (olivines), and magnetite (iron oxides). In terms of oxide proportions, the Ysson analog lies in-between a high-Ti mare regolith and a low-Ti mare regolith.

Morphology and particle size distribution of the Ysson analog powder: Regolith particles do not undergo erosion: space weathering, meteoritic impacts, and thermal expansions are the prevailing phenomena that are responsible for their irregular shape, far from a perfect sphere. To guarantee physical properties as close as possible to the regolith studied, the Ysson analog has been mechanically ground. The morphology (Figure 1) and the chemical composition of the ground particles were characterized thanks to SEM observations and EDS analysis. Grain size distribution of the ground powder has been measured too and compared to that of Apollo 11, 12, 14, and 15 samples [5], using laser diffraction analysis.

¹ ISRU : In-Situ Resource Utilization

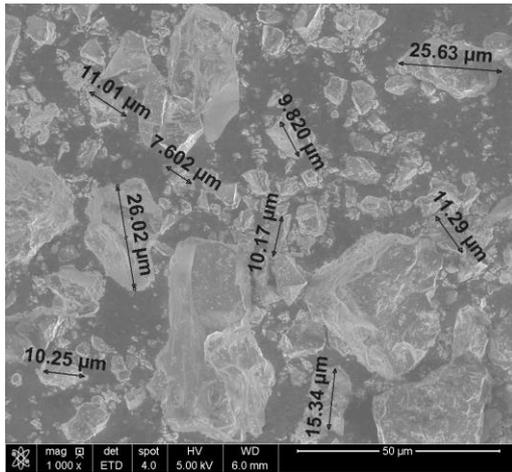


Fig 1: Morphology and size of Ysson analog particles (SEM observation)

Thermal, thermomechanical, and thermo-optical properties of the Ysson analog: During the SLM process, the interactions between the laser (i.e. a monochromatic light source centered at a wavelength of $1\mu\text{m}$) and the analog powder must be assessed over a wide temperature range [6]. The optical response of the Ysson analog is then measured in terms of reflectivity and absorptivity as a function of the temperature with a FTIR spectrometer (from room temperature to 400°C) and a specific bench for emissivity measurement (up to 1000°C). The part of energy absorbed by the regolith is then thermally diffused to the rest of the powder, hence the necessity to estimate the density and thermal conductivity of the analog, and determine the specific heat with the help of a well-established model [7]. Yet, working at high temperatures also induces numerous phase changes (e.g., melting, sintering, ...), that all affect previously overlooked properties. DTA and TMA have been used to find characteristic transition points during a first thermal cycle (Figure 2). They present particularly a remarkable endothermic peak centered at 1150°C and a drastic shrinkage of the sample in the same temperature range. This indicates a sintering of the Ysson analog at such a temperature level.

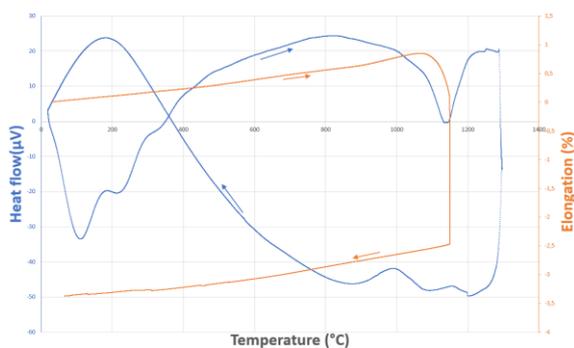


Fig 2: DTA and TMA curves of Ysson analog during a first thermal cycle

Early SLM tests: Preliminary SLM tests have already been done on Ysson analog non-sieved powder, with a unique layer being laser. The effects of the variation in laser power, scanning speed, hatching distance and laser spot size have been assessed. The resulting energy surface density has been ranged from 3.6 to 250.0 J/mm^2 , showing significant microstructural variations. As these tests were mainly carried out to demonstrate the feasibility of the additive manufacturing process, the intrinsic mechanical properties of the lasered material have not yet been fully determined. Multi-layered SLM trials will be conducted, allowing the manufacture of bending / tensile test pieces.

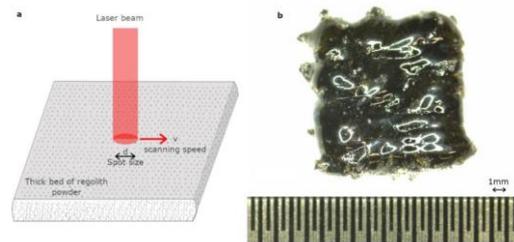


Fig 3: Sketch of the process and top view of a lasered Ysson analog powder

Perspectives: The Ysson analog is not intended to match perfectly the regolith of any given location on the Moon such as a future landing site, but rather to serve as a basis for exploring and documenting the effect of compositional changes on the properties previously mentioned. Once this base analog fully characterized, modifications on phase proportions and nature will be investigated by oxide doping and adding amorphous particles (to address the potential influence of natural glassy components present in the lunar regolith) prepared from the same material. The implementation of a general methodology and a physical model for the SLM process relevant for any encountered regolith or any operating temperatures is the driving objective of this work.

References: [1] Isachenkov M. et al. (2021) *Acta Astronaut.*, 180, 650–678. [2] Taylor L. et al. (2016) *Planet. Space Sci.* 126, 1-7. [3] Gibilaro M. et al. (2021), “ISRU taskforce in Toulouse”, NESF-ELS. [4] Souchon A. L. et al. (2011) *Icarus*, 215, 313–331, [5] Carrier W. D. (1973) *The moon* 6, 250-263 [6] Goulas A. et al. (2016), *Rapid Prototyping Journal*, 22(6), pp.864-870 [7] Schreiner S. et al. (2016) *Advances in Space Research* 57, 1209–1222