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3D PRINTING OF MOON HIGHLANDS REGOLITH SIMULANT

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The purpose of this paper is to evaluate the feasibility of 3D printing of Moon regolith simulant specifically selected to have a similar composition to that of Lunar Highland Terrain type. This work is a validation of the results already obtained by other researchers with the simulant JSC-1A and serve the purpose to provide wider knowledge on the *additive manufacturing* of Moon in-situ resources using the simulant NU-LHT-2M. The technology adopted in this study is the Selective Laser Melting (SLM) supported by granulometry analysis of the powder with SEM imaging and microanalysis of the material before and after processing to assess the chemical composition variation and structure modifications. The properties of the printed parts were tested using a Vickers micro-indenter, a hydraulic press coupled with a load cell and a thermo-vacuum chamber.

The results obtained confirm the feasibility of SLM with Moon Highlands regolith simulant using energy densities ranging from 2.96 to 4 J/mm² obtaining small printed parts with surface hardness of ~ 695 HV and compressive strength of ~ 22.7 MPa suggesting possible future applications in the fabrication of objects and, if opportunely scaled, even small buildings.

Keywords: 3D Printing, Additive Manufacturing, regolith simulant, NU-LHT-2M, exploration, colonization, selective laser melting

1. Introduction

The renewed interest in the Moon exploration and colonization is driving increasing efforts in finding profitable solutions for the construction of an inhabitable outpost on our natural satellite. Both private companies and national agencies are funding the research for a permanent base but there are no currently available solutions.

The main constraints on the realization of a human outpost on the Moon are related to the shear costs of launching extremely heavy machinery or structures to be directly used or installed on the lunar surface. The most appealing solution is the use of Additive Manufacturing (AM) processes that can make use of the Moon resources to create anything needed for the construction of buildings or spare parts. Some researchers already obtained results on the feasibility of 3D printing with the moon dust [1][2] but the technology is not ready for a demonstration flight lacking the complete knowledge of the parameters needed for different type of lunar soil. The researches performed are focused on the use of Moon mare simulants (mainly JSC-1A) while some of the regions of scientific interest are located on the highlands. Among the technologies used in the previous studies the most suitable for this research is the powder bed fusion (PBF) with the use of a fiber laser as energy source. Following the re-

sults obtained by Goulas et al. [3][4] and Fateri et al. [5][6], this work focused on the selection of the most appropriate set of laser parameters to obtain printed parts from raw regolith simulant powder using as test material NU-LHT-2M. A restraint defined at the beginning of this work was the use of the least possible amount of pre-processing of the material in order to verify to which extent the process can adapt in adverse conditions.

The use of 3D-printed material for building purposes must be supported by experimental evidence of the mechanical properties useful for this objective. In the previous works the majority of the tests were conducted on the material density and the surface hardness without considering the interest arising from the knowledge of other mechanical properties such as the compressive strength. In this work surface hardness and overall quality of the products are studied to offer a comparison with the previous results, but the study is completed by investigating the effective material resistance to compressive loads.

The work presented in this article was divided in 3 steps focusing on the properties of the raw material, the process parameters search and the printed parts testing respectively.

2. Material preparation

The first part of this work focused on the analysis of the properties of NU-LHT-2M that could potentially be more critical for the SLM process; after receiving the batch, the main interest was towards the

granulometry and the presence of water in the powder due to exposition to uncontrolled atmosphere during previous tests. To avoid as much as possible the contamination due to water presence, the solution was to put the batch in a thermovacuum chamber for 24 hours after which it was kept in silica sealed containers. Water presence proved afterwards hard to completely avoid but the experiments were not compromised by the small residues left in the powder used.

The second major issue related to the material properties was the size of the grains present in the batch that should have been an average of $100\mu m$ with maximum values around $1mm$ while the results obtained with a *Malvern Mastersizer 2000* showed a slightly shifted value towards $250\mu m$. Aside from the results, some larger grains were later found making mandatory a quick preprocessing before loading the machine, comprising hand sieving and visual inspection of the material used. The results of the granulometry analysis are reported in Fig. (1) and include 5 different runs and their average. The inclusion of an automated sieving process may improve the quality of the powder and lead to increased precision and repeatability of the printing, but in this work one of the goals was to determine how much adverse condition, also in terms of material quality, could impact on the feasibility of the process, thus the sieving was performed only when the size of the grains were such to completely prevent the machine from operating correctly.

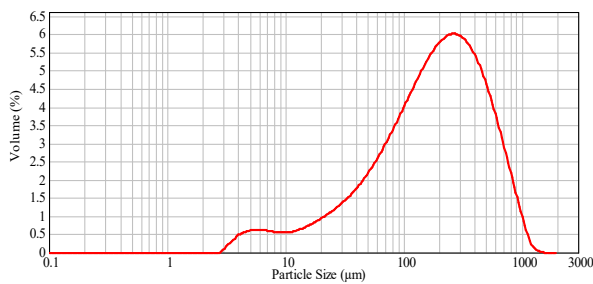


Figure 1: Granulometry analysis of the NU-LHT-2M received

Chemical composition and reflectance are values reported in the NASA documents on the certification of NU-LHT-2M and were assumed correct and considered only to evaluate an initial theoretical feasibility of the process with the given laser wavelength and power.

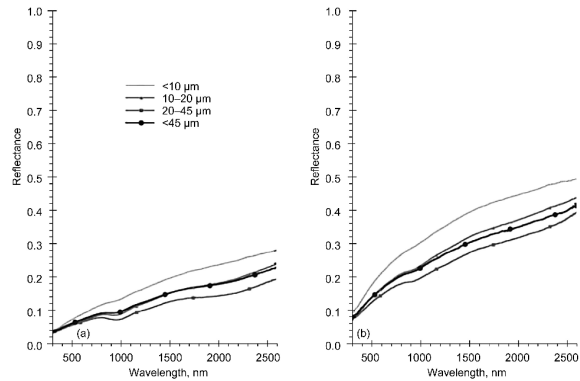


Figure 2: Reflectance of Moon Sample of mare soil (a) and highlands soil (b) from Apollo missions sorted by grain size (Data from NASA research [7])

Using a $250W$ fiber laser at $1070nm$ proved in previous works capable to efficiently melt the JSC-1A simulant and produce solid 3D-printed objects working at about 20% of its maximum power; the values of reflectance at the desired wavelength are not enough dissimilar to justify the choice of another type of laser so it was not changed in this work. At the same time the chemical composition of the two simulants should differ since they are designed to be similar to the soil of different regions of the Moon but the knowledge of some of the major components of the powder offers possible hints on the fine adjustments to apply for a better process. Table(1) reports the mass percentages of various elements present in the NU-LHT-2M simulant and compares them to that of actual Moon soil samples returned to Earth during the Apollo missions.

	Apollo 16	NU-LHT-2M
SiO_2	45.09	46.60
TiO_2	0.56	0.115
Al_2O_3	27.18	21.55
FeO	5.18	5.65
MnO	0.065	0.09
MgO	5.84	9.50
CaO	15.79	12.60
Na_2O	0.47	0.965
K_2O	0.11	0.12
P_2O_5	0.12	0.07
Cr_2O_5	0.107	0.12
S	0.064	-
LOI^*	-	2.74

Table 1: Chemical composition comparison between NU-LHT-2M and Apollo 16 samples
 Note: *LOI, lost in ignition volatiles

3. Printing process

After defining the most relevant properties of the powder, the printing process was tested using a small size SLM prototype capable to operate either in soft vacuum or inert atmosphere. The choice to use the laser in an oxygen deprived environment (Ar atmosphere was used) was made in order to avoid the combustion of small particles and the consequent damages that the process could cause to some of the most sensible components of the machine. The machine flexibility was exploited in terms of the material used as substrate for the printing process. The possibility to interrupt and adjust the process during operation was an extremely valuable resource in order to obtain good results. The machine main parameters are reported in Table (2).

Parameter	Value
Power (max)	250W
Wavelength	1070 nm
Laser spot size	75 μm
Scanning speed	50-250 mm/s
Hatching space	75-150 μm
Layer thickness	150-250 μm

Table 2: SLM machine parameters values used in the tests

The first tests were based on a wide range of parameters that offered a general knowledge on the material response to the processing with the laser source. Power, scanning speed, hatching space, thickness of the layers and focal point offset were tested in various combination to evaluate which set of parameters returned the best results but the process didn't return any positive results due to lack of adhesion of the printed material to the substrate. The steel plate used showed extremely low wettability to NU-LHT-2M as can be seen by the balling effect visible in Fig.(3) but the problem was faced selecting other materials, including various metal alloys that showed the same balling effect; the best results were obtained with a ceramic substrate.

The substrate chosen for the test is a refractory clay commonly used for high temperature oven or kiln, thus capable to withstand the large amount of thermal energy exchanged during the process and, at the same time, having a chemical composition closer to that of the powder used. The possibility of coating the metal substrate with a thin layer of the NU-LHT-2M was discarded due to higher costs and difficulties of implementation in the process.

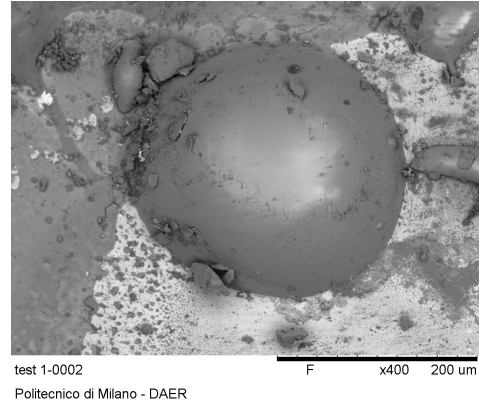


Figure 3: Balling effect on the steel substrate

Once the substrate was substituted with the refractory clay plate, the experiments proceeded without issues related to the adhesion of the powder, but the laser power was reduced drastically to avoid damages to the ceramic substrate. After investigating the possible combination of parameters, the best results in terms of consistency of the printed part quality and precision were obtained with the parameters reported in Table 3.

Laser Power	50 – 60	W
Laser Spot	50 – 300	μm
Scanning Speed	100 – 200	mm/s
Layer Thickness	150	μm
Hatching Space	75	μm
Duty Cycle	100%	-

Table 3: Final set of parameters chosen for the printing of NU-LHT-2M

The printed objects were small cubes with size of 5mm arranged on the substrate in a checkerboard pattern to separate the results depending on the parameters used for each of them. During the final prints, the position linked to each parameters set was random in order to avoid any interference on the quality related to geometry parameters. The results were in no way affected by the geometry but in one run, during which the substrate was slightly misaligned and the growth of the pieces was not uniform across the plate.

4. Results

After the range for each parameter was defined, a set of printed samples were produced to test the material mechanical properties. The first step after removing the pieces from the substrate was to measure each of them to grant repeatability of the tests without introducing any correction factor. Afterwards, the pieces were put in a thermovacuum chamber to remove any volatile component trapped

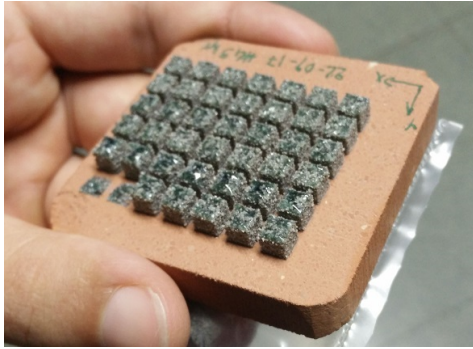


Figure 4: Printed parts obtained with the final set of parameters

inside the molten powder. The procedure adopted was described in the ECSS normative as the bake-out processing of parts to be used in the outgassing tests for space components. The printed objects were exposed to $T \geq 125^\circ\text{C}$ and $P \leq 1\text{Pa}$ for a total time of 16 hours to ensure that all the volatile components were removed.

The first test was performed on a mixed batch of samples to evaluate the surface hardness through Vickers microindentation following the procedure described in the ASTM [8]. In order to have smooth parallel surfaces to work on, the parts were enclosed in a resin cast which also offered a better support during the test. The pieces were polished using increasing sandpaper grit, from P60, to P120 and finished with P320.



Figure 5: Specimens in the resin cast

The specimens were tested in a Leica VMHT30A, set to 500gf load with a 15s dwell time repeating the analysis for each sample in 10 discrete position on its surface to avoid any sort of bias in the measurements. The average result for the surface hardness of the material for each specimen is reported in Table 4 showing results in the order of the hardness of common silica glass as obtained in the researches involving JSC-1A.

Sample N.	HV
A50200	679.28
A50225	680.93
A55200	669.51
A55225	698.39
A60200	690.57
A60225	661.75
B50200	673.51
B50225	638.16
B55225	748.54
B60200	710.43
B60225	685.43

Table 4: Average hardness for the different samples

One of the lacking information on the 3D-printing with Moon regolith simulant is the compressive strength of the material, which in this study is introduced but requires further developments to return precise results applicable to the actual building process with 3D-printed moondust. In this research the strength was measured using a load cell coupled to a hydraulic press imposing a displacement value on the moving head. The material showed fragile behaviour, as expected for ceramics, and a strength comparable to that of concrete, reaching average yielding stresses as reported in Table 5

	σ_Y [MPa]
A50200	16.6
A50225	31.43
A55200	22.3
A55225	29.55
A60200	14.34
A60225	22.24

Table 5: Yield Stresses

One interesting phenomenon was observed in every run of the compressive strength test, during which the material started yielding but didn't collapse as expected and, instead, was compacted. The internal crevices created during the melting and rapid cooling of the material offer an energy relief thanks to the inner structure that can be exploited as a ballistic protection system, for example against impact with small objects and micrometeorites, typical of the Moon environment and currently one of the potential hazards that could be found on the lunar surface during the colonization process.

5. Conclusions

This research proved the feasibility of 3D-printing with highlands regolith simulant NU-LHT-2M, addressing one of the missing point of previous researches, limited to the use of mare regolith

simulants. The values obtained shows that the behaviour of the different simulants is similar under many point of view, including also the mechanical properties obtained during the analysis of the printed parts. This work is a starting point for a more extensive research on the properties of the materials used and the capabilities of the SLM technology applied to space exploration and colonization. Next steps in this work will comprise thermal analyses and radiation shielding properties investigation on printed objects, together with an increase in the TRL of the machine used which could be scaled and adapted to be space certified and approved for a flight demonstration or even an IOD mission.

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