Fused Layer Deposition of Lunar Regolith

Executive summary

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Authors: **Miranda Fateri, Juan Carlos Ginés Palomares** (Hochschule Aalen, Germany)

Alexander Niecke, Tongzhou Wiedehage (RWTH Aachen, Germany)

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Advenit Makaya
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Introduction

In order to enable lunar exploration in a sustainable manner, it is necessary to develop technologies that allow the use of lunar resources in-situ. Additive manufacturing techniques are being studied for in-situ resources utilization on the Moon (e.g.: solar or laser sintering). The results of these studies, presented samples with low mechanical properties due to the formation of defects and cracks within the final product.

Lunar regolith is a mixture of crystalline and amorphous material (glass). The degree of vitrification of glassy products highly depends on the respective cooling process. In this project, the implementation of the annealing process during printing is proposed. The annealing process consists on the control of the cooling process from the glass transition temperature to room temperature in order to minimize the internal stresses inside the material and reduce the defects formed during cooling down.

Lunar FLD Concept

For this project, the used of Fused Layer Deposition (FLD) with lunar regolith simulant as raw material is explored. FLD is an Additive Manufacturing technique which consists on the fabrication of parts by extruding the molten material in a layer wise manner.

In order to avoid the crack formation in the final product, the layers are extruded inside an annealing chamber. This enables controlling the cooling rate of the printed parts, leading to the relaxation of internal stresses inside the glass structure.

The Lunar FLD printer consists of three basic elements:

- The printer head: It is composed by the bushing, where the material is heated up (by means of an induction coil) until it is molten, and the nozzle for the extrusion of the material.
- The annealing chamber: It is a kiln which holds the annealing temperature during the printing of the samples. The manufacturing process takes place inside of this component.
- The printing platform: It moves inside the annealing chamber in x-y-z directions.

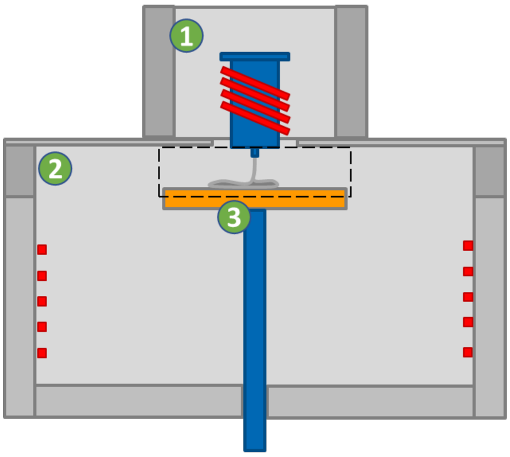

Figure 1. Components of the printer's concept. (1) Print head, (2) Annealing chamber, (3) Printing platform.

Material

The selected material for this study is EAC-1 lunar regolith simulant which is developed by the European Astronaut Centre (EAC) in Cologne, Germany.

A set of experiments were performed with the Hot Stage Microscope (HSM) and a viscosity model calculation (*Bottinga & Weill 1972*) in order to obtain the characteristic working temperatures of the material.

For the HSM analysis, the sample of EAC-1 was heated up from room temperature to 1400 ºC at 10 ºC/h. During the process, pictures of the sample's outline were taken by a camera. Finally, the changes on the area and shape factor of the sample were analysed as an indicator of the simulant's melting behaviour. The flow temperature of the material is measured to be approximately 1250 °C.

In addition, the HSM experiment was performed with ITALUS1 simulant as well, giving the result of 1225 ºC (similar to EAC-1A).

Lunar FLD Printer

The 3D printer is placed on a supporting structure. The mechanical elements responsible for moving the building platform are placed below the annealing chamber, sealed and separated by a stainless-steel plate from the annealing chamber. These include: 7 guides (4 for the movement in the vertical axis z, 2 for the movement on the horizontal axis y and 1 for the movement on the horizonal axis x), 4 stepper motors (2 for the z-axis, 1 for the z-axis and 1 for the x-axis).

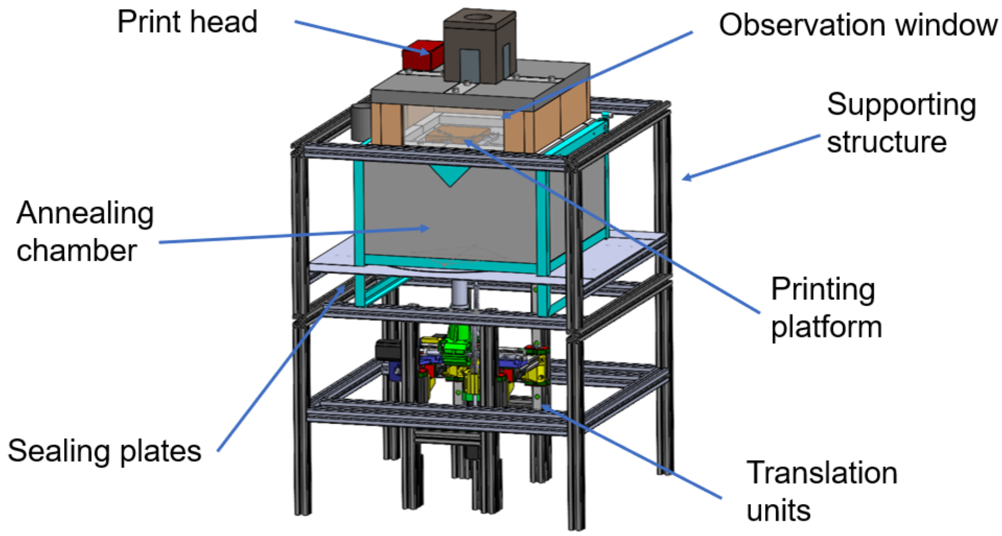

Figure 2. CAD design of the Lunar FLD printer.

The print head is placed atop of the annealing chamber, supported by a vermiculite structure that works as insulating material. This can be removed to have access to the interior parts. The crucible and nozzle used in this project is made out of a Platinum-Rhodium alloy. This component is heated up by means of an induction coil. In addition, observation of the printing process is enabled by integration of two transparent windows, made of Neoceram glass-ceramic. The electronic control of the system is done by a Duet 2 control board. The different components are wired to the board and the pre-designed software is adapted and used for the managing of the printings.

Experiments and results

Initial printing trials have been successfully carried out for E-glass as E-glass is easily available and has similar viscosity properties as ITALUS-simulant. During the printing trials, different processing parameters have been optimized, including the printing speed, the layer thickness and the extrusion height. A set of 9 experiments were conducted to determine the layer thickness of the samples when changing the printing speed of the experiments. For each printing speed, the experiments were performed three times. Below, a graph with the results of these experiments can be found.

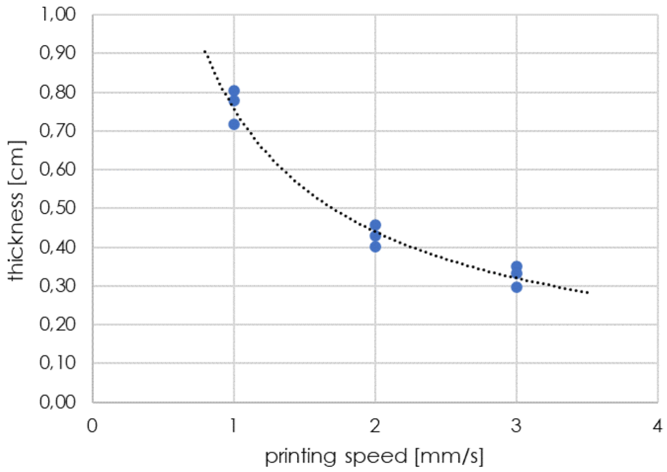

Figure 3. Layer thickness and printing speed of the samples.

Among the manufactured samples, in **Figure 4** two of them are highlighted. On the left, a cylindrical rod is obtained from a vertical extrusion line of the material flow when cooling down. On the right, a spring-like sample is printed without support structures, the lines of material do not touch each other in this geometry. This could indicate an advantage of this kind of 3D printing over traditional 3D printing using polymers and needs to be further investigated.

Figure 4. Two of the samples manufactured.

In another printing campaign, several cubic samples with 100% infill ratio were successfully printed. The next set of experiments consisted performing printing tests with EAC-1 lunar regolith simulant, aiming to print the same geometries that were already fabricated with e-glass. The Initial extrusion trials of the EAC-1 simulant has unfortunately failed. The nozzle was clogged due to crystallization of EAC-1 melt at the nozzle tip. It was concluded that the uniformity of the temperature reached in the extrusion unit (crucible + nozzle) is important to have a suitable material flow. If the temperature of the molten material falls below a certain value (1000-1150°C for EAC-1), partial crystallization of the melt occurs and the viscosity is increased to a point in which the material extrusion is not possible. This occurred in the nozzle tip of while extruding the EAC-1 simulant. A temperature difference of up to 250°C was measured during trials as can be seen in **Figure 5**. An increase in power input to remelt the crystallized nozzle proved to be ineffective, as the nozzle did not reach the required temperature.

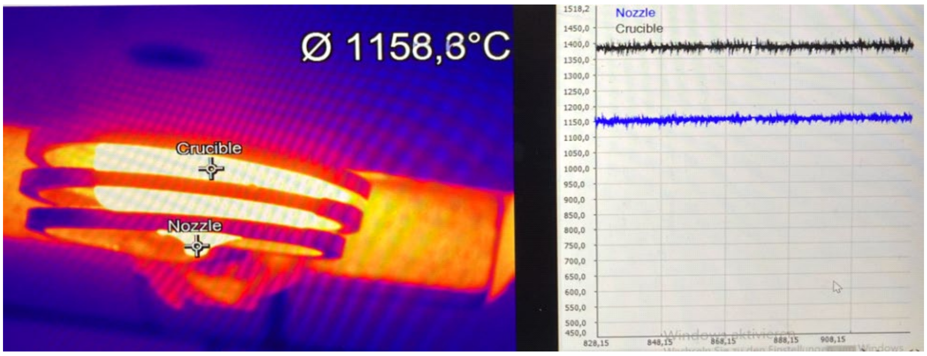

Figure 5. Temperature difference between crucible and nozzle during trials with EAC-1.

As a solution (for the further investigation on the nozzle blockage topic) to the nozzle blockage problem, the team proposed to change the used lunar regolith simulant in the printing tests and performed additional experiments with ITALUS simulant instead of EAC-1. This was done due to the similarities in of ITALUS simulant's viscosity to the E-glass. Initial trials using the ITALUS simulant proved to be also ineffective due to the clogged nozzle (as was previously seen by extrusion trials of EAC-1 simulant). It was concluded that, the blockage of the nozzle could be related to the iron-content of the basaltic mixture. Higher iron-content of the basaltic mixture compared to E-glass results in a much higher heat radiation of heat in the crucible, leading to a relatively high temperature gradient in the nozzle. It was concluded that, for basaltic mixtures, a specially designed induction coil needs to be developed to increase the energy input of the extrusion tip of the crucible. A schematic of such a design is shown in **Figure 6**.

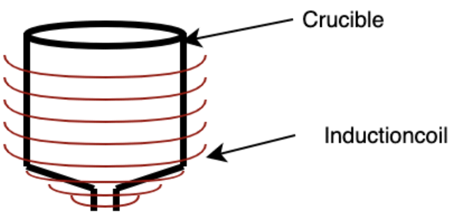

Figure 6. Schematic drawing of a narrowing induction coil that follows the geometry of the crucible.

Initially, the annealing procedure was planned to be tested with E-glass (see -**Figure 7**-A. Initial printing and annealing trials have shown that, the build chamber could be preheated up to 400 °C. After 400 °C. the heating rate of the oven became very slow and led into technical problems. The low heating rate of the chamber was found to be due to heat loss of the printer unit. Also, the cooling pipes of the induction coil were overheated.

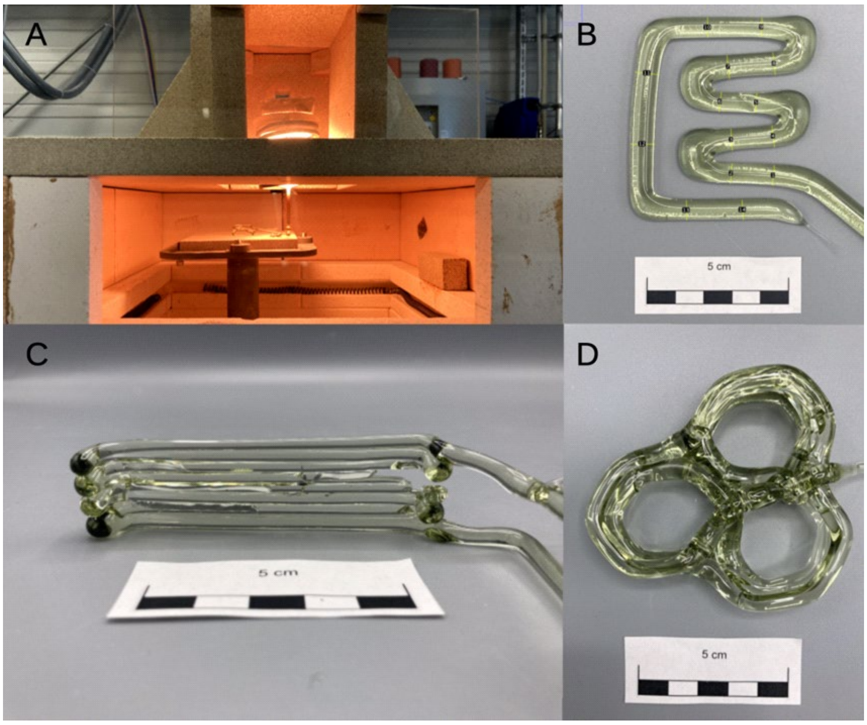

Figure 7. Using e-glass. A: 3D-Print in progress, B: structure for evaluation of printing parameters, C: 8-layered wall structure, D: hexagonal structural print.

As such, the annealing process could not be extensively tested due to the current design of the printing unit. These problems need to be addressed by increasing the isolating capabilities of the printer in general, either by using thicker or different refractory materials.