Molten Regolith Extrusion (MREx): Additive Manufacturing Experiments in Vacuum

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Introduction: Establishing a sustained human presence on the Moon requires infrastructure for radiation shielding and landing pads. Shipping materials from Earth is mass-prohibitive, making In-Situ Resource Utilization (ISRU) essential. Molten Regolith Extrusion (MREx) is a binderless additive manufacturing process that melts lunar regolith and deposits it via gravity [1]. Unlike laser-based methods, MREx leverages mechanical simplicity and passive material flow, which are critical for reliability in harsh environments. While previous studies focused on atmospheric trials, this work evaluates the MREx process under vacuum conditions.

Experimental Setup and Methodology: The MREx experiments were conducted within a vacuum chamber at TU Berlin as part of the 3D-LAVA project. The experimental setup (see Fig. 1) utilizes a resistively heated furnace/printhead (see Fig. 2) to heat lunar regolith simulant (here: LX-M100 mare simulant [2, 3]) within a crucible to temperatures exceeding its liquidus range. Once the material is fully molten, it is extruded via gravity through a nozzle at the bottom of the furnace. This allows for both stationary casting and layer-by-layer deposition on moving substrate inside the vacuum chamber. To characterize the process, the temperature of the extruded melt is measured using a pyrometer (5.14 µm) and a thermal camera (7.9 µm). These measurements provide critical data on the transition from viscous flow to solidification, allowing for a detailed analysis of the annealing behavior and structural integrity of the resulting glass-like parts.

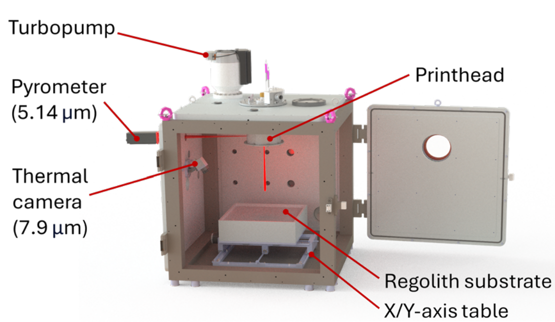

Fig. 1: Rendering of the experimental setup.

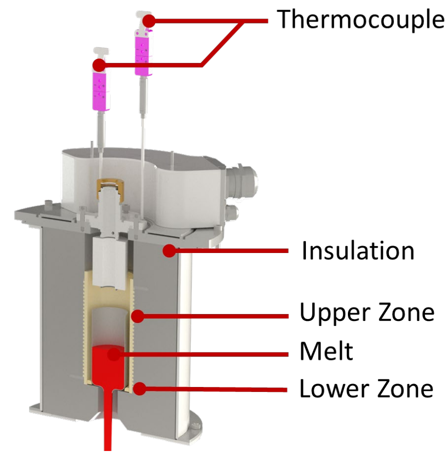

Fig. 2: Cross-section of the high-temperature printhead.

Results and Discussion: The feasibility of the MREx process was evaluated through an extensive series of experiments involving varied substrate materials, temperature profiles, and translation stage movement patterns. While specific trials demonstrated the ability to form continuous structures, the transition to a high-vacuum environment revealed complex physical behaviors and thermal constraints that dictate the quality of the final parts. By analyzing data across these diverse parameters, several key findings regarding the fluid dynamics and solidification of molten regolith were identified:

- The molten regolith undergoes a free-fall phase after exiting the nozzle where the viscous thread is subject to gravitational acceleration and surface tension before reaching the deposition surface.
- Upon contact with the substrate, the downward-moving melt experiences longitudinal compressive stress that triggers a helical buckling instability known as the liquid rope coiling effect.
- The coiling motion is categorized into four distinct regimes (viscous, inertial, inertial-gravitational, and gravitational) based on the dominant physical forces acting on the fluid thread during its fall and impact [4].
- The viscosity of lunar regolith melts is temperature-dependent and has been studied for a wide range of simulants.

- Excessive heating leads to a viscosity drop that is too low to maintain shape and results in the melt flowing or slumping after deposition (Fig, 3).
- Radiation-dominated cooling in a vacuum environment results in significantly lower heat loss rates compared to the convective and natural cooling observed in terrestrial air experiments.
- Gas formation and ebullition within the melt create internal porosity and structural defects that occur independently of the specific feedstock material.
- Cooling rates in recent experiments remain excessively high and cause the material to shatter due to unrelaxed internal stresses (See. Fig. 4).
- Accurate temperature control is hindered by the lack of spectral emissivity data which causes significant discrepancies in pyrometric measurements during the phase transition.

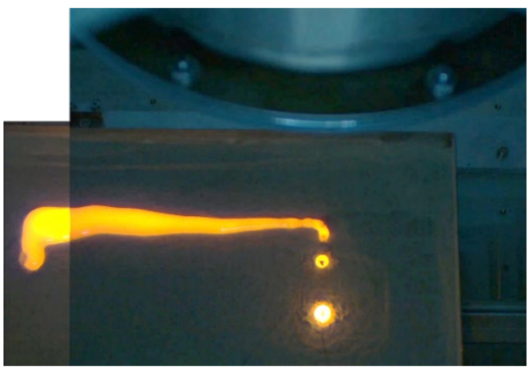

Fig. 3: Extrusion on a moving bed (squared motion, a = 200 mm).

Fig. 4: Extruded sample after cooling inside of the vacuum chamber.

Conclusion and Future Work: The experimental trials within the 3D-LAVA project demonstrated that Molten Regolith Extrusion is a functional method for additive manufacturing in vacuum. However, the process requires significant refinement to become a reliable construction technique. The vacuum conditions changed the process dynamics in a fundamental way. While the lack of convective cooling was expected to help, the radiative heat transfer was still too fast. This caused the parts to break despite the slower overall cooling rate in the chamber.

The research showed that feedstock preparation and substrate selection are critical. Issues such as bubbling, degassing, and the formation of pores [5, 6] must be resolved to achieve structural integrity. A better annealing strategy is necessary to manage the internal stresses that lead to fracturing [7]. An induction furnace is currently being integrated into the system to allow for much quicker process cycles. Future work will focus on investigating the in-situ annealing to prevent the samples from breaking during the cooling phase.

During the Space Resources Roundtable, more information on this process and the underlying physics will be shared. This includes the analysis of the Liquid Rope Coiling Effect during extrusion and a perspective about the feasibility of executing this process on the Moon.

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