

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

DLP 3D Printing of High Dense Lunar Regolith Ceramic Parts

LAUREA MAGISTRALE IN SPACE ENGINEERING - INGEGNERIA SPAZIALE

Author: GIOVANNI CAPPELLARI Advisor: Prof. Antonio Mattia Grande Co-advisor: Maxim Isachenkov Academic year: 2024-2025

1. Introduction

The pursuit of sustainable space exploration and long-term lunar habitation has brought increased attention to In-Situ Resource Utilization (ISRU) as a means to reduce the reliance on Earth-supplied materials. One of the most promising technologies for this application is additive manufacturing (AM), which allows for the fabrication of functional components directly on the lunar surface using local materials. Among the various AM techniques, Digital Light Processing (DLP) 3D printing has gained interest due to its high precision, ability to create complex geometries, and suitability for ceramicbased materials.

This study builds upon prior research on DLPbased additive manufacturing of regolith simulants by introducing new sintering conditions, an extended analysis of heating rates, and the addition of boric acid and silica fibers as sintering modifiers and reinforcements.

The primary goal was to improve the mechanical properties, densification, and microstructural integrity of regolith-based 3D-printed components while maintaining process feasibility for potential ISRU applications.



Figure 1: Complex 3D printed geometries

By optimizing key sintering parameters and studying the influence of additives, this research aimed to determine the most effective processing conditions for fabricating regolith-based components capable of withstanding harsh lunar environments. The study contributes to a growing body of work that seeks to bridge the gap between material science, lunar engineering, and AM technologies, making lunar manufacturing a tangible possibility.

2. Methodology

The research methodology was designed to evaluate how different processing parameters affect the mechanical, microstructural, and densification properties of DLP-printed lunar regolith simulants. The study examined three distinct material compositions:

1. Standard regolith (0% BA) based on LHS-1 simulant, was chosen due to its

chemical and mineralogical similarity to lunar highlands regolith. The standard formulation consisted of 70 wt% regolith powder and 30 wt% other chemical components, aligning with the optimal mix previously identified in the literature.

- 2. Boric acid-modified regolith (2,5/5% BA), where 2.5 wt% and 5 wt% boric acid were incorporated before the milling process to act as a sintering aid and improve densification. Boric acid was selected due to its low melting point and ability to enhance glass phase formation, which can reduce porosity and promote grain bonding.
- 3. Fiber-reinforced regolith (0,5% Fb), incorporating 0.5 wt% silica fibers, which were blended separately and then added to the pre-made slurry to improve mechanical strength and fracture resistance. The fiber content was kept low to prevent processing issues, given their mechanical defects and tendency to induce porosity at higher concentrations.

After material preparation, specimens were printed using a DLP 3D printer, maintaining a layer thickness of 50 µm.



Figure 2: 3D printed samples before and after sintering

Samples were subsequently sintered at five different temperatures 1100°C to 1300°C with 50°C intervals. Six different heating rates were tested: 0.5° C/min, 1°C/min, 0.5-1°C/min, 2°C/min and 4°C/min.



Figure 3: Sintering curves of the runs

A comprehensive mechanical and microstructural characterization was performed using:

- Flexural and compressive strength tests, to evaluate load-bearing capabilities and structural performance.
- Vickers hardness testing, performed with a Future Tech FM-810 microhardness tester using a 500g load at the center of each sample.
- Relative density measurements, conducted via the Mohr-Westphal hydrostatic balance method.
- Shrinkage analysis, performed using imageJ software and considering both dimensional shrinkage (ΔL) and mass loss (Δm) during sintering.
- Microstructural observations using SEM and EDX, to analyze the distribution of additives, fiber retention, and densification behavior at different sintering conditions.

These tests provided a detailed picture of how processing conditions influence mechanical properties, densification, and structural reliability, forming the basis for the study's key findings.

3. Results

3.1. Effect of Sintering Temperature and Heating Rate

The results confirm that sintering temperature is the dominant factor influencing densification and mechanical performance. At 1250°C, samples exhibited optimal densification, with relative densities exceeding 94%, while porosity was significantly reduced. An additional test at 1300°C achieved the highest density (96.17%), but the improvement in flexural strength was marginal, while compressive strength experienced a significant drop, suggesting excessive grain growth leading to structural weakening.



Figure 4: Compressive strength of standard regolith across different sintering temperatures and heating rates

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The heating rate had a notable effect on mechanical performance but not on final density. The best flexural and compressive strength values were achieved at 0.5°C/min, while faster heating rates introduced higher residual stresses and lower mechanical integrity, likely due to nonuniform grain growth and insufficient time for structural relaxation.



Figure 5: Flexural strength of standard regolith as a function of sintering heating rate at 1250°C

3.2. Effect of Boric Acid as a Sintering Modifier

The incorporation of boric acid significantly enhanced densification and mechanical performance.



Figure 6: Flexural strength as a function of boric acid concentration at different sintering temperatures

The 5 wt% boric acid composition achieved the highest relative density, while the 2.5 wt% boric acid composition exhibited slightly higher flexural strength. Vickers hardness results showed that both compositions outperformed standard regolith, with 5 wt% boric acid yielding the highest values.



Figure 7: Relative density of boric acid-modified and fiber-reinforced regolith as a function of sintering temperature

3.3. Effect of Fiber Reinforcement

The addition of silica fibers did not improve mechanical performance as expected. SEM images confirmed non-uniform fiber distribution, with some areas exhibiting fiber clustering, while others had low fiber concentration.



Figure 8: Flexural strength of fiber-reinforced regolith across different sintering temperatures

After sintering, many fibers had fused into the matrix, which negatively impacted porosity and overall strength. This suggests that the chosen fiber type was not thermally stable under the given sintering, leading to its degradation rather than reinforcement. Moreover, the mechanical defects of the fibers likely impacted the overall performance of the final component.

3.4. Microstructural Analysis and Hardness Testing

• Shrinkage measurements confirmed that dimensional contraction increased with temperature, though the heating rate had minimal influence.



Figure 9: Linear shrinkage (ΔL) of boric acidmodified and fiber-reinforced regolith as a function of sintering temperature

• Porosity reduction was directly linked to sintering temperature, with boric acidmodified samples showing the lowest porosity values.



Figure 10: Porosity of boric acid-modified and fiber-reinforced regolith as a function of sintering temperature

• Vickers hardness increased with sintering temperature, with boric acid-modified regolith consistently outperforming the standard formulation.



Figure 11: Vickers Hardness of boric acidmodified regolith as a function of sintering temperature

4. Conclusion

This research demonstrated the viability of DLP 3D printing for regolith-based ceramics, emphasizing the importance of optimized sintering conditions for achieving high mechanical performance and densification. The 1250°C sintering temperature with a 0.5°C/min heating rate proved to be the best condition, balancing density and mechanical properties. Boric acid was confirmed to be a beneficial sintering aid, improving microstructural integrity and mechanical strength, while silica fiber reinforcement proved ineffective, warranting further investigation. For future research, efforts should focus on:

- Exploring alternative fiber reinforcements (e.g. boron carbide fibers, nickel-coated carbon fibers) to achieve actual strengthening.
- Expanding sample size to reduce statistical variability and confirm observed trends.
- Testing in lunar-like conditions, including vacuum sintering and thermal cycling, to assess performance under real extraterrestrial environments. Using actual lunar soil instead of simulants could also improve the reliability of the reuslts

The findings of this study contribute to the growing field of additive manufacturing for lunar ISRU, supporting the long-term goal of self-sustaining lunar infrastructure and construction technologies.