Sintering of Lunar Regolith Simulant in Vacuum by Microwave Sintering for ISRU Construction

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Introduction: NASA plans to return humans to the lunar surface and establish a sustained human presence on the Moon for the foreseeable future [1]. More countries than ever are joining the space exploration program with a focus on establishing a sustainable lunar presence and conducting lunar exploration. To support long-term sustainable lunar surface exploration and continuous human presence, infrastructure (e.g. long-duration habitation and ISRU plant) is necessary [2].

Our research aims to develop the underlying technology needed to build the infrastructure. The ideal approach to producing construction materials on the lunar surface would be to utilize In-Situ Resource, lunar regolith, and microwave heating has been proposed as a suitable method for sintering lunar soil on the Moon [3-9].

In this study, we focused on manufacturing construction blocks in a vacuum environment using microwave sintering. Optimal sintering conditions, such as preheat treatment, temperature, and heating rates were determined to obtain uniform sintered samples in vacuum. We expect that microwave sintering is a promising method for in-situ construction to establish landing pads, roads, and human habitats.

Materials and Methods: In this study, KLS-1, which is a lunar mare regolith simulant, was used. KLS-1 was sieved through a no. 20 sieve (<850 μm) before microwave sintering. Microwave sintering was performed in a multi-mode microwave furnace operating at 2.45 GHz (Fig. 1). The microwave cavity consisted of a SiC susceptor, an insulation box, and a thermocouple. A microwave-transparent quartz tube, containing 35 g of KLS-1, was located in the center of the heating zone and connected to a vacuum line. During the sintering process, the temperature inside the heating zone was measured, and the controller adjusted the microwave power by comparing the desired temperature. The maximum output power of magnetron is 1 kW. To remove moisture from the lunar regolith simulant, KLS-1 was pretreated at 500°C. After reaching a vacuum degree of 1×10^{-2} mbar at 500°C, the lunar regolith simulant was heated at 1080, 1100, and 1120 °C for 15 min under vacuum, respectively. The sintered samples were obtained after cooling to ambient temperature.

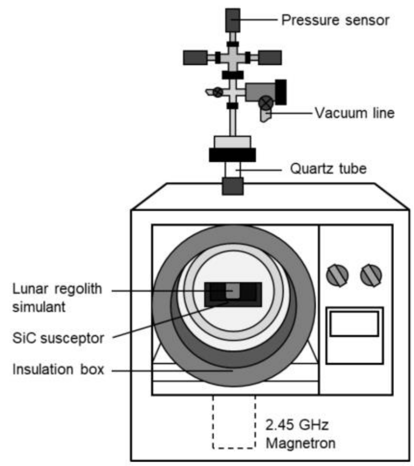

Fig 1. Schematic diagram of a microwave furnace. Microwave sintering of lunar regolith simulant was performed under vacuum in a quartz tube

Results and Analysis: Fig 2. shows the pressure and temperature profiles during the microwave sintering process. According to the simultaneous thermal analysis–mass spectrometry results of KLS-1, most of the moisture in KLS-1 is emitted below 500°C. Since the moisture in KLS-1 can cause soil disturbance during the depressurization process and lead to cracks in the sintered body, a pretreatment process was carried out to remove the moisture by heating the simulant to 500°C in air for 1h and then depressurizing at the same temperature. After reaching a vacuum of 1×10^{-2} mbar at 500°C, samples were then sintered under vacuum for 15 min at 1080, 1100, and 1120 °C, respectively. High heating rate might cause non-uniform sintering, so microwave heating was carried out using a slow heating rate of below 5°C/min. During the sintering process, there was a rise in pressure observed in the temperature range of approximately 600 to 900 °C, which was due to gases generated from the samples. Further research is needed to determine the composition of the outgas.

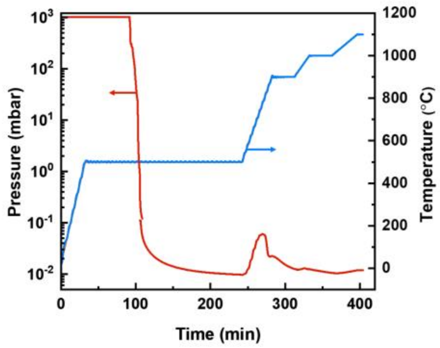

Fig. 2 Pressure and temperature profiles during the microwave sintering process

Fig. 3 presents photographs of sintered samples in air and vacuum, respectively. The diameter and height of the sintered sample are 25 mm and 30 mm, respectively. The color of the sample sintered in air appears reddish (Fig. 3a), while the color of the sample sintered in vacuum appears dark gray (Fig. 3b-d). These color differences are expected to be caused by the difference in the oxidation state of iron oxide. Previous studies have shown that olivine, one of the constituent minerals of KLS-1, oxidizes with oxygen in air to produce hematite (Fe_2O_3) and magnetite ($MgFe_2O_4$) phases [7]. Under vacuum conditions, the oxidation reaction is minimized, resulting in gray sintered samples. It can be seen that the samples sintered at 1080°C and 1100°C result in cylindrical shaped sintered bodies, while the sample sintered at 1120°C results in a non-uniform shaped sample. In addition, many pores of various shapes and sizes are observed on the outside of the sample sintered under vacuum at 1120°C, as shown in Fig. 3c. It is expected that when sintering at 1120°C, some molten parts of the sample were vaporized under vacuum, resulting in many pores within the sintered body.

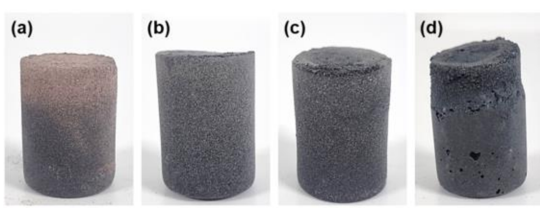

Fig.3 Images of lunar regolith simulant microwave sintered at (a) 1080 °C in air, (b) 1080°C (c) 1100°C, and (d) 1120 °C under vacuum.

Conclusion: In this study, microwave sintering of the lunar regolith simulant (KLS-1) was performed at 2.45 GHz at various temperatures (1080-1120°C) under vacuum. Optimal sintering conditions such as preheating treatment, temperature, and heating rate were determined. To obtain uniform sintered bodies, the KLS-1 was preheated at 500°C and sintered up to 1100°C at a low heating rate (3-5°C/min). It was observed that sintering samples at temperatures above 1120°C resulted in sintered samples with non-uniform shape and many pores. We will discuss in detail the effect of sintering temperature on density, porosity, and mechanical properties.

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