Microwave Sintering of a Lunar Soil Simulant: Effects of Sintering Conditions on Microstructure Evolution and Micromechanical Properties

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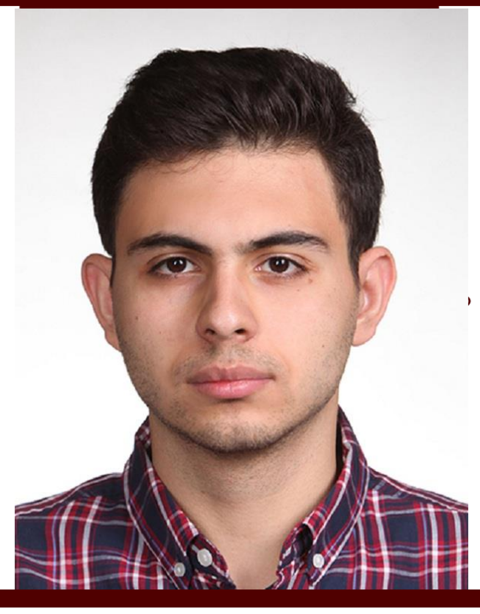
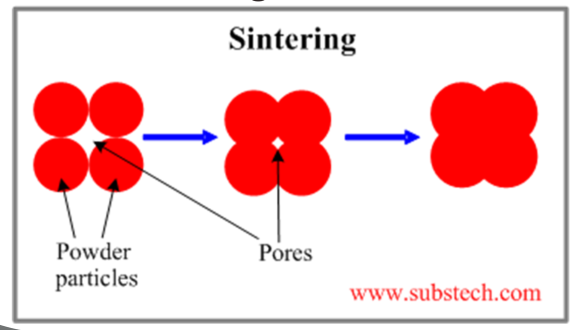
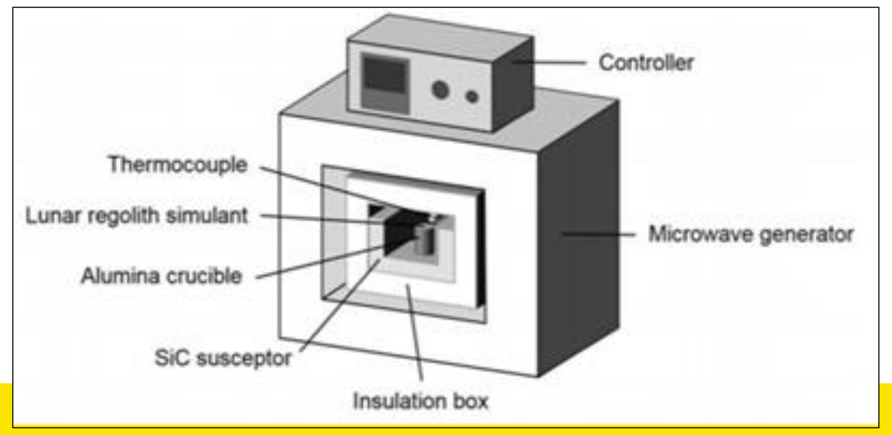


Objectives and Motivation

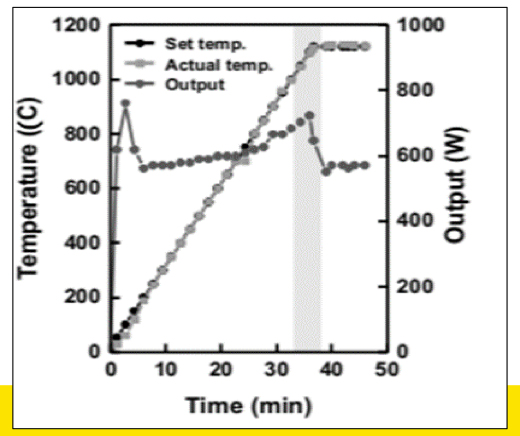
In-situ resource utilization (ISRU) is an important concept in deep-space exploration and space architecture. Advanced manufacturing techniques such as sintering could be implemented in ISRU-based construction. The goal of this research is to investigate the feasibility of the Microwave Sintering (MS) method to build structural components out of lunar regolith for aerospace applications. MS employs an instantaneous volumetric heating and consumes significantly lower amounts of energy than the conventional oven or laser sintering techniques. Laboratory tests were conducted to optimize the sintering conditions (temperature, dwell time, and heating rate) and to assess evolution of mechanical properties and phase transformation of sintered lunar regolith.



ISRU Construction



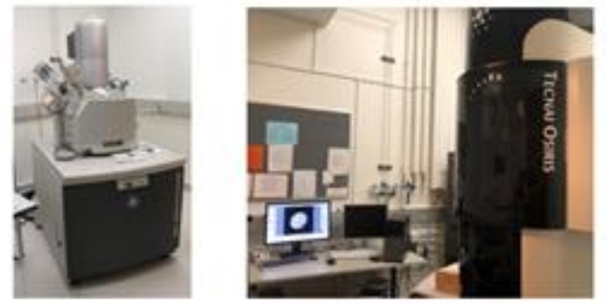
Microwave Sintering Schematic



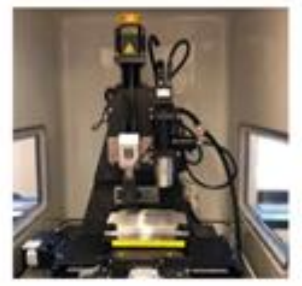
Energy Consumption

Analysis Methods

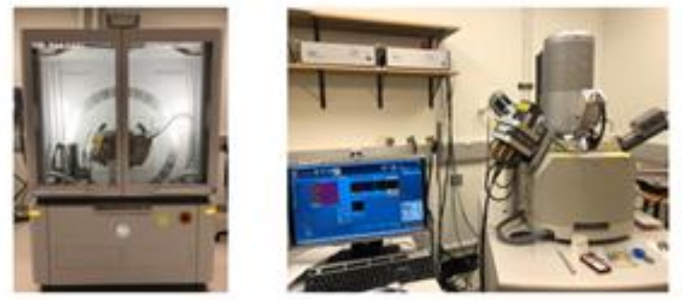
- Imaging (microstructure): SEM, TEM

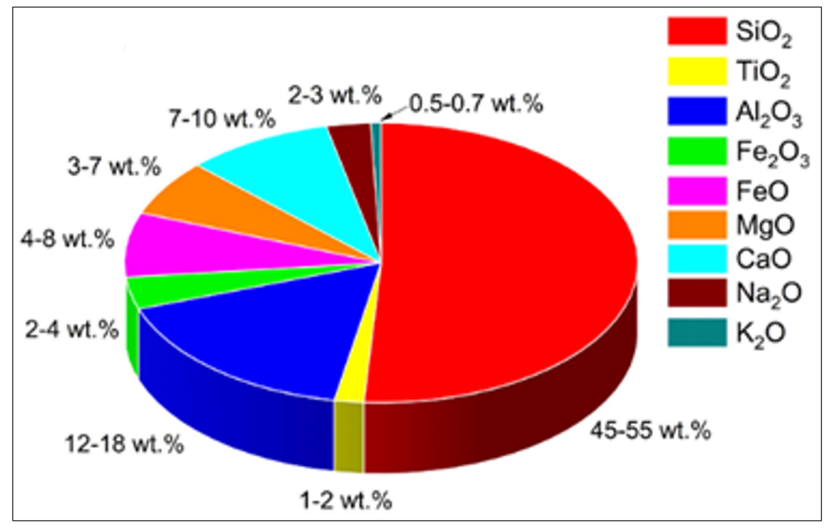


- Nanoindentation (mechanical properties): Hysitron Tribology

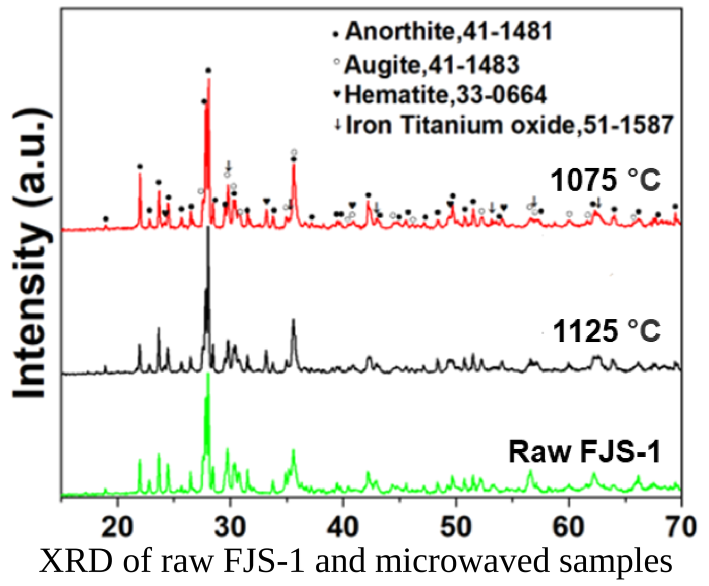


- Chemistry: XRD, EDS

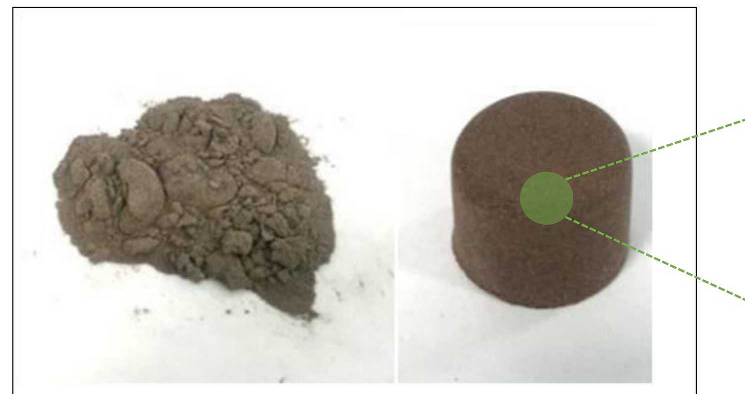




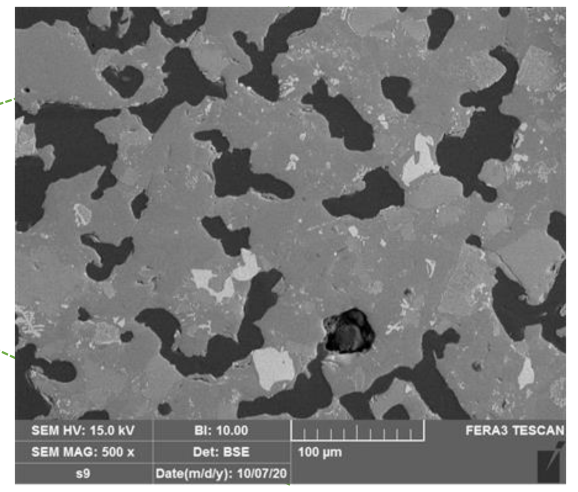
Chemical composition of FJS-1



XRD of raw FJS-1 and microwaved samples

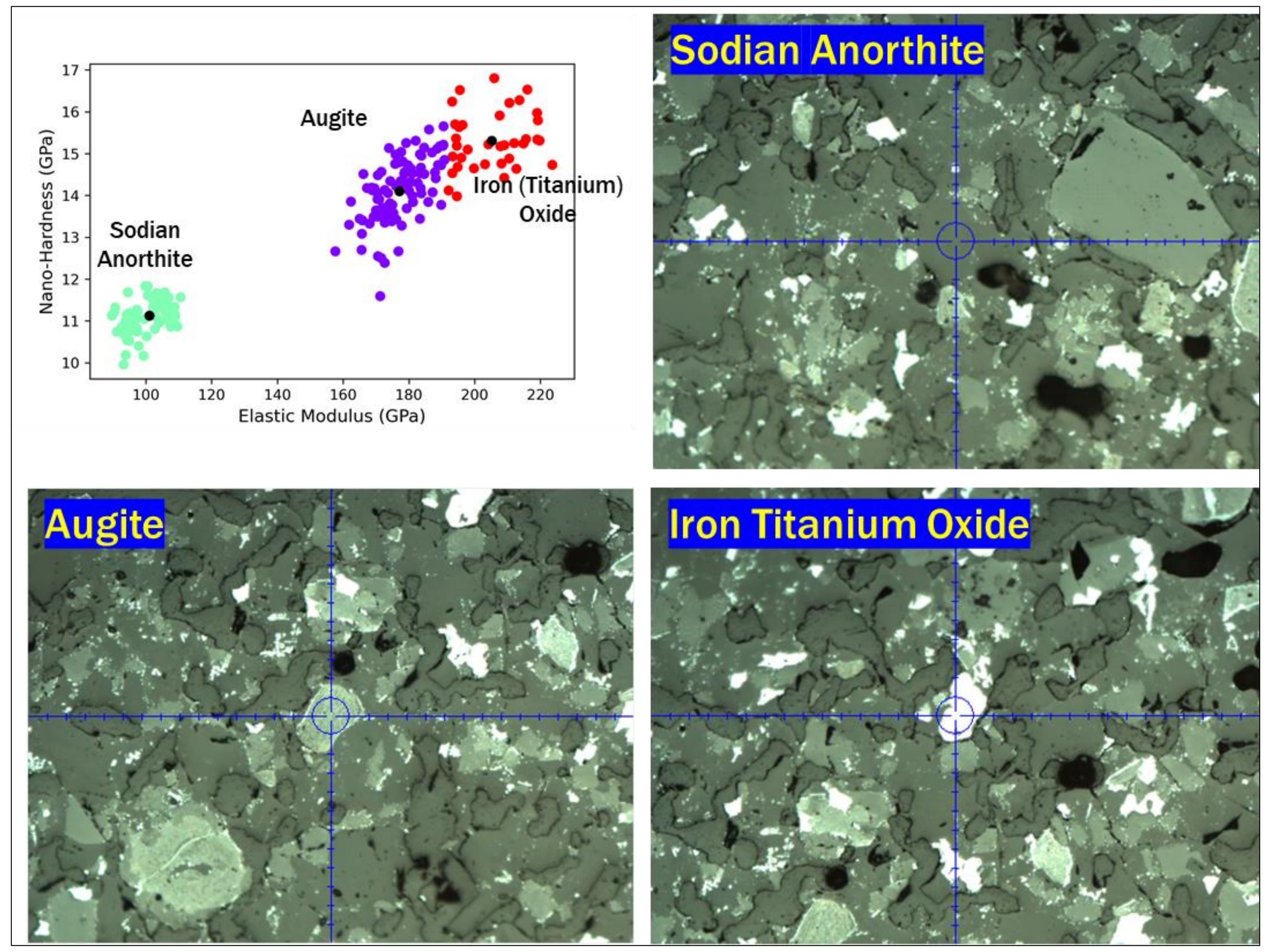


Microwave sintering at 1000 °C vs. 1100 °C

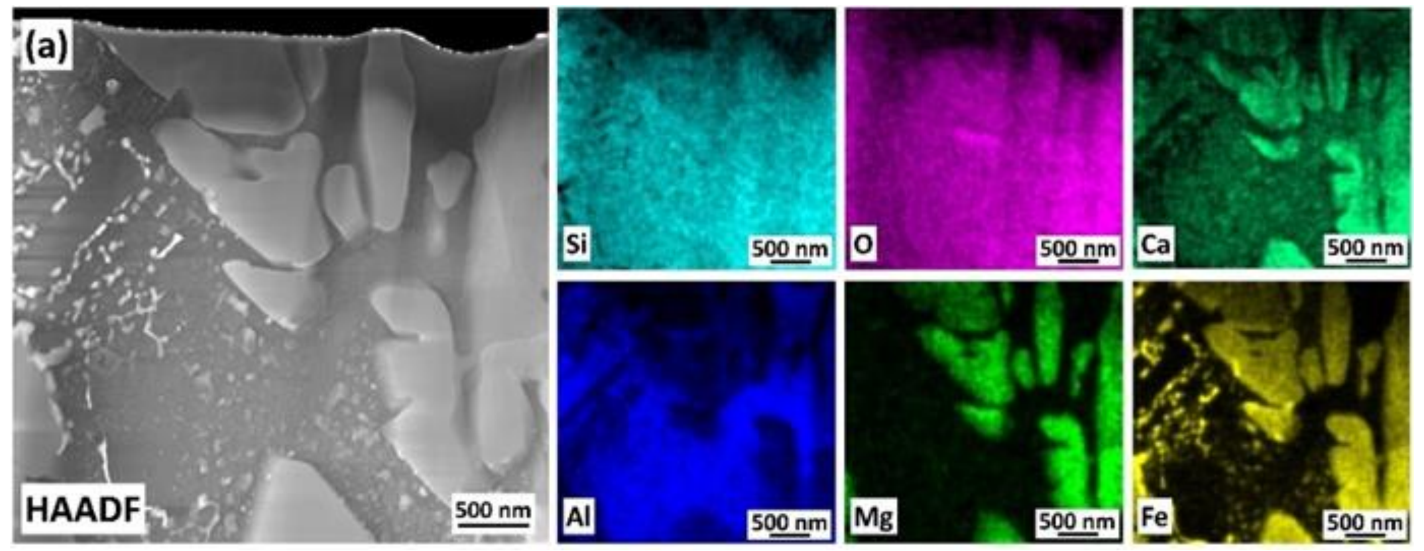


Morphology with backscattered electron microscope

Specimen ID	Sintering Temperature (°C)	Dwell Time (min)	Heating Rate (°C/min)
MS1	1075	10	30
MS2	1075	5	25
MS3	1075	20	20
MS4	1100	20	30
MS5	1100	10	25
MS6	1100	5	20
MS7	1125	5	30
MS8	1125	20	25
MS9	1125	10	20



MS1 micro-mechanical properties



TEM-HAADF image of MS1 with EDS mapping of Si, O, Ca, Al, Mg, and Fe elements

Results

- Microwave sintering was not effective up to 1050 °C, and rigid samples could only be fabricated at higher temperatures. Heating rates higher than 30 °C/min induced non-uniform heating and thermal gradient.
- The Taguchi design method was efficient and successful to examine the effects and sensitivity of testing parameters where a L9 orthogonal array was selected and signal to noise ratios per each level of each factor was determined. Sintering temperature was the dominant factor.
- TEM-EDS analysis determined that silicon, aluminum, and calcium were dispersed in entire sample while iron and magnesium were dispersed only in some components. The following phase transformation was introduced:

$(Ca,Na)(Si,Al)_4O_8 + (Fe,Mg,Ca)SiO_3 \rightarrow Ca(Mg,Fe,Al)(Si,Al)_2O_6 + NaAlSi_2O_6 + SiO_2$

- Chemical and micro-mechanical studies demonstrated three major peaks of elastic modulus which were correlated with three mineral phases: Soidan Anorthite with higher volume fraction (>70%) and lower elastic modulus (50-100 GPa), Augite and Iron Titanium Oxide with lower volume fraction and higher elastic modulus (>100 GPa). Higher concentration of Iron and Titanium Oxide resulted into stiffer micro-components.

Findings

- Among the three microwave sintering variables considered in this study, sintering temperature was the dominant factor determining final stiffness and porosity reduction during the MS process.
- The sintering conditions affected the overall physical properties. However, stiffness of each micro-component did not change significantly.
- The collective results indicate that microwave sintering could densify the lunar regolith simulant to fabricate a structural component and could be identified as a potentially viable ISRU method.