Microwave Heating Studies and Instrumentation for Processing Lunar Regolith and Simulants

M. Barmatz[1], D. Steinfeld[1], D. Winterhalter[1], D. Rickman[2], M. Weinstein[3], [1]Jet Propulsion Laboratory, California Institute of Technology, M/S 79-24, 4800 Oak Grove Drive, Pasadena, CA 91109, E-mail: Martin.B.Barmatz@jpl.nasa.gov, [2]MSFC-ZP11, Huntsville, AL 35812, [3]Zybek Advanced Products, Inc., 2845 29th Street Boulder, CO 80301.

Introduction: An earlier study of the lunar regolith [1] demonstrated that the lunar surface soil was an extremely good absorber of microwave energy. Since then, efforts have been made to understand the mechanism for that exceptional absorption. It was speculated that the presence of nanophase iron was the unique component causing this absorption, however, our recent measurements on lunar soil samples and simulants [2,3] suggested that this might not be the case.

It is known that micrometeorite impacts caused shock melting of lunar regolith leading to vaporization and re-condensation. This process has produced pieces of broken lunar rock and glassy *agglutinates* whose particles show sharp, jagged edges. The objective of this study was to evaluate whether the presence of a significant number of sharp-edged particles in a lunar simulant will enhance the microwave absorption of a sample. It is known that sharp edges of a sample heated in a microwave oven will tend to focus the electromagnetic fields leading to enhanced local heating. If these tests prove positive, the procedure used to obtain these sharp edged particles can be applied to produce new lunar simulants needed for evaluating how to efficiently process the lunar regolith. Validating the importance of sharp-edged particles in enhancing microwave heating could also have important commercial applications.

Microwave Measurements: We studied two types of lunar simulants, a highland Chenobi composition and a mare JSC-2A composition. For the highland composition, we compared a well-characterized Feldspar (Anorthosite) rich simulant with about 70% angular and very angular particles to the same sample material after being processed in a ball mill for 1 hour to significantly reduce the number of angular and very angular particles. The resultant materials were passed though 100 mesh and 200 mesh screens to obtain 74 μm to 149 μm particles for microwave testing. The mare compositions consisted of basalt rich simulant samples that were also prepared in the same manner.

Microwave studies were carried out at frequencies near 2.45 GHz. The room temperature resonant frequency and quality factor of the rectangular cavity's TE_{103} – TE_{104} modes measured with and without the sample inserted, were used to determine the permittivity and permeability from a cavity perturbation approach [4].

The sample densities were determined by weighing the sample holder with and without the sample inserted. The TE_{103} mode (frequency = 2.161 GHz) determined the permittivity and the TE_{104} mode (frequency = 2.444 GHz) determined the permeability. The measured values are shown in Table I for samples with sharper particle edges and in Table II for samples with rounder particle edges. In comparing the magnitudes of the complex permittivity, ε'', for both the sharper and rounder particle samples, we find that the mare sample values are over 3 times larger than the highland values, which is consistent with the measured heating curves, see Fig. 1. Similarly for the complex permeability, μ'', for both sharper and rounder particle samples, we find the mare sample values are ~ 2 to 4 times larger, again consistent with the heating curves, see Fig 2.

We also directly heated the simulant samples using a TWT microwave amplifier and compared their heating properties. These measurements were performed in the same microwave cavity used for the permittivity and permeability measurements. To accomplish this heating study, we assembled a high power microwave

Table I. Complex Permittivity and Permeability of highland and mare simulant with sharper particle edges.

	Highland (Sample density)	Mare (Sample density)
ε'	2.50 (1.16 gm/cc)	2.95 (1.42 gm/cc)
ε''	0.0109	0.0372
μ'	1.01	1.00
μ''	0.0011	0.0021

Table II. Complex Permittivity and Permeability of highland and mare simulant with rounder particle edges.

	Highland (Sample density)	Mare (Sample density)
ε'	2.51 (1.20 gm/cc)	2.98 (1.43 gm/cc)
ε''	0.0110	0.0383
μ'	1.00	1.01
μ''	-0.0003	0.0011

facility. The distinguishing feature of this facility was a frequency tracker that tracked the resonant frequency during heating to maximize power transfer into the cavity. The test sample was situated in a small quartz holder that was inserted at the center of the microwave cavity. The sample temperature was monitored through a hole in the top of the cavity using a non-contact IR sensor. A LabVIEW program recorded the sample temperature and microwave parameters (forward power, reverse power, cavity diode voltage, and resonant frequency) versus time during the heating process. With this information, we could determine which material was more efficiently heated.

We microwave heated both the highland samples and mare samples using ~ 60 Watts going into the cavity. All samples were initially outgassed at 200 C for 3 hours. The sharper mare and highland particle samples were magnetically heated more efficiently than the rounder particle samples as shown in Fig. 1. The mare samples showed a higher magnetic heating rate than their corresponding highland samples. The dielectric heating of all samples, shown in Fig. 2, was much faster, reaching higher temperatures, than found for the magnetic heating. This result is consistent with earlier predictions [2] and with measurements shown in Tables I and II. The dielectric heating of the highland

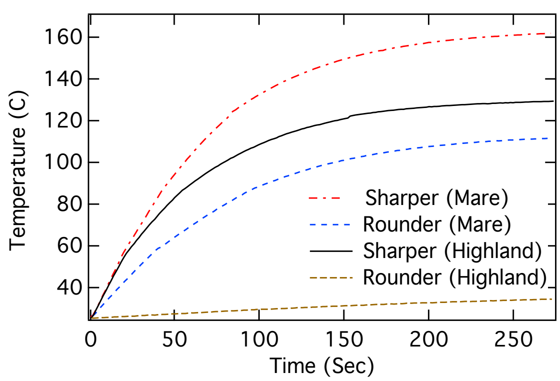

Fig. 1. Magnetic Heating of simulant samples

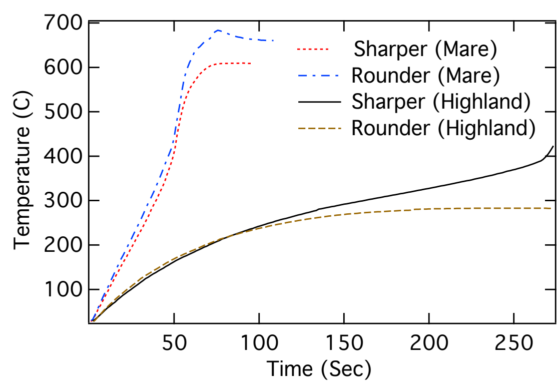

Fig. 2. Dielectric heating of simulant samples

samples also showed a higher heating rate for the sharper particle sample. However, the dielectric heating rate of the mare rounder particle sample was slightly higher than for the mare sharper particle sample.

The most unexpected and distinguishing feature of these mare dielectric runs was the increase in heating rate occurring above ~ 400 C. In our experimental arrangement, there was a sudden change the reflected power behavior occuring around 400 C that led to a significant reduction in the power level in the cavity. We associate this behavior with a material property change such as melting or formation of a new composition. This transformation could initially occur at the center of the sample where the temperature could be much higher than the surface temperature due to a large temperature gradient produced by volumetric microwave heating. This enhanced heating behavior is also seen just beginning in the highland dielectric run around 400 C, see Fig. 2. Repeating the dielectric heating of the highland sample using 100 Watts led to the same enhanced heating curve as found for the mare samples, see Fig. 2. The samples showing this behavior would heat to significantly higher temperatures if the initial power level in the cavity were held constant.

These new detailed microwave heating measurements on lunar simulants have revealed an enhanced heating effect that may be the main mechanism responsible for the previously observed exceptional microwave heating of the lunar regolith [1]. We are now analyzing the microstructure of the processed samples to determine the components causing this effect. The results of this study are important because taking advantage of enhanced heating may lead to microwaves being the most economical way to process the lunar soil for use in future efforts to colonize the moon. Our measurements have shown that magnetic heating of highland and mare as well as dielectric heating of highland lunar simulants is enhanced for sharper particle samples over rounder particle samples.

Acknowledgement: This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration and funded through the internal Research and Technology Development program.

References: [1] Taylor, L.A., and Meek, T.T., (2005), *J. Aerosp. Eng.* **18**, 188-196. [2] Barmatz, M., Steinfeld, D., Begley, S.B., Winterhalter, D., and Allen, C., (2011), *Lunar Planet. Sci.* ***42***, Abstract #1041. [3] M. Barmatz, D. Steinfeld, D. Winterhalter, D. Rickman, R. Gustafson, D. Butts, and M. Weinstein, (2012), *Lunar Planet. Sci.* ***43***, Abstract #1050. [4] 85071-300 software for Agilent E8364B Network Analyzer; ASTMD 2520, Method B.