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Appendix A: Microwave Heating of Lunar Materials

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Introduction

Microwave heating of nonmetallic inorganic material has been of interest for many years. Von Hippel in the late 1940s and early 1950s investigated how microwave radiation up to 10 GHz couples to various insulator materials. Perhaps the most work has been done by Wayne Tinga at the University of Edmonton (Alberta, Canada). Most of the work to date has been done at the two frequency bands allowed in industrial use (0.915 GHz and 2.45 GHz). However, some work has recently been carried out at 28 GHz* and 60 GHz (Meek et al. 1986). At Los Alamos National Laboratory, the work has centered about the fabrication of useful engineering components.

Table A-1 lists some materials that have been thermally processed using microwave energy and some products that have been fabricated at both 2.45 GHz and 60 GHz.

*Personal communication with H. D. Kimrey, Fusion Energy Division, Oak Ridge National Laboratory.

TABLE A-1. *Some Starting Materials Heated by Microwave Energy at Los Alamos and Resultant Products*

Material	Product	Processing temperature, °C	Frequency, GHz
Owens-Illinois (OI)—1756C glass	Ceramic-glass seal	462	2.45
OI—0038 glass	Ceramic-glass seal	735	2.45
1613 glass**	Ceramic-glass seal	1450	2.45
Alkali basalt	Sintered material	1200	2.45
Al_2O_3	Sintered material	1300-1900	2.45, 60
ZrO_2	Sintered material	1300-1900	2.45, 60
Ilmenite	Sintered material	1350	2.45
Apollo 11 regolith	Sintered material	1100	60
SiC whisker-Al_2O_3	Composite material	1300-1900	2.45, 60

**High-temperature glass made at Los Alamos.

Using microwave energy to process lunar material offers a new, potentially very efficient way of heating these types of materials. Not only can lunar material be heated with less energy than that required by conventional methods, but the heating is accomplished more uniformly and in much less time (Meek et al. 1985).

Discussion

Many oxide materials are transparent to microwave energy at 2.45 GHz and 0.915 GHz. Oxides that possess impurities, such as mobile ions or mobile defects, that enhance their electrical conductivity will, however, couple to electromagnetic radiation in this frequency range. Heating will be primarily electronic.

For example, beta alumina contains by weight 11 percent sodium, thus enabling it to couple efficiently to 2.45 GHz microwave radiation. Beta alumina, when placed in a 2.45 GHz microwave field of 400 watts power can be heated from room temperature to its sintering temperature (1850°C) in just a few seconds (Berteand and Badot 1976). Materials such as cuprous oxide (Cu_2O), zinc oxide (ZnO), and zirconium dioxide (ZrO_2) will also couple efficiently because they are defect-controlled semiconductors. To heat traditional oxide materials, such as alpha alumina, we incorporate materials that do couple to 2.45 GHz radiation, such as aluminum nitrate. These materials cause the oxide to heat to a few 100 degrees Celsius, after which the oxide will couple because its ability to absorb electromagnetic energy (its loss tangent) has increased sufficiently.

It is known that most lunar regolith, down to a depth of 3 meters, contains at least 10^6 imperfections per cubic centimeter from cosmic rays, solar flares, and the solar wind (see fig. A-1). The defects introduced into this soil over millions of years' exposure to these high-energy particles should increase the loss tangent of this material and allow it to be heated in a microwave field without the use of coupling agents. Terrestrial alkali basalt shows only weak coupling initially; however, when the intensity of the electric field is increased, this material heats rapidly. Recently we demonstrated the ability to heat ilmenite to its melting temperature using 2.45 GHz microwave energy. Since ilmenite is present in abundance on the lunar surface in mare regions, it could act as a coupling agent to allow the initial heating of those lunar materials that may not couple at ambient temperature.

Figure A-1

Tracks of Cosmic Ray Particles and Solar Flare Particles in a Plagioclase Crystal

The plagioclase crystal structure has been severely damaged where these high-energy particles have penetrated into the crystal. Etching of the crystal with NaOH has preferentially removed the damaged material, leaving elongated, rectangular holes or tracks. Such track damage is common in many lunar regolith crystals.

Table A-2 shows observed heating rates for some of the materials thermally processed using 2.45 GHz and 60 GHz microwave energy. If the proper electric field intensity (E) or magnetic field intensity (H) is used, rapid heating of lunar materials will also occur. The following expression (Püschner 1966) shows the relationship between the approximate heating rate and the applied electric field intensity for the heating of an insulator material.

$$\dot{T} = \frac{8 \times 10^{-12} f E^2 k' \tan \delta}{\rho C_p}$$

where $\dot{T}$ = heating rate in degrees Celsius per minute
f = frequency in hertz
E = electric field intensity in volts/cm
k' = dielectric constant of the material
$\tan \delta$ = loss tangent of the material
ρ = density of the material
C_p = heat capacity of the material

Because heating on the Moon will occur in a vacuum, where much greater electric field intensities can be used, materials that would not couple on Earth may be heated very easily and quickly.

TABLE A-2. *Heating Rates Observed for Different Insulator Materials Heated at 2.45 GHz and 60 GHz*

Material	Observed heating rate, °C per hour	Frequency, GHz
1613 glass	33 000	2.45
OI–0038 glass	20 000	2.45
OI–1756C glass	12 000	2.45
Aluminum oxide	18 000	60

Recommendations

Much work remains to fully characterize some of the phenomena observed to date with microwave-heated oxide and composite materials. For example, diffusion should be modeled, reaction kinetics should be studied, and sintering kinetics should be better understood.

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