Single Mode Microwave Heating of Copper Powder Metal Compacts

J. Ma, C.T. Smith, G.J. Weisel, B.L. Weiss, N.M. Miskovsky, D.T. Zimmerman*
The Pennsylvania State University, Altoona College, Altoona, PA 16601
*Corresponding author: 3000 Ivyside Park, Altoona, PA 16601; Email: dtz1@psu.edu

Abstract: We present numerical simulations that complement our experimental results of the microwave heating of copper powder metal compacts in separate electric (E) and magnetic (H) fields of a TE102 cavity. In general, thermal dissipation in the compacts may be attributed to resistive heating, dielectric losses, and magnetic losses. These dissipative mechanisms are coupled to the fields by the effective conductivity, effective complex permittivity, and effective complex permeability of the compacts, respectively. We model the fields of the cavity and the heating trends of the compacts by incorporating the separate losses into COMSOL using independently measured values of the electromagnetic parameters. The simulation results show good agreement with experimental ones and help to provide a self-consistent picture of the interaction of microwave fields with powdered metals.

Keywords: Microwave heating, powder metallurgy.

1. Introduction

Microwave heating and sintering of various high dielectric loss materials such as oxides and carbides has been widely studied and applied in different industrial applications [1, 2]. Compared with conventional furnace where heating is due to convection, microwave furnace provides a more rapid and efficient way of heating and sintering. Furthermore, such a rapid heating limits grain growth during sintering and thus help to improve microstructure and mechanical properties of the sintered products.

It was reported in 1999 by R. Roy and coworkers [3] that porous metal powder compacts heat when subjected to microwave irradiation in either electric (E) or magnetic (H) antinodes despite the well known fact that microwave does not penetrate bulk metals beyond skin depth and thus can not heat metals in a microwave furnace. R. Roy's results show that the porous metal powder compacts are materials have both effective dielectric and effective magnetic losses corresponding to effective permittivity and effective permeability of the porous metal compacts. Together with the effective electrical conductivity, these three factors account for the heating of these porous metal compacts in microwave.

In this paper, we present the experimental heating behaviors of porous copper powder metal compacts heated in both E and H antinodes of a single mode TE102 cavity working at 2.45GHz, the measurements of effective conductivity using four points measurement method as well as effective complex permittivity and effective complex permeability of the compacts using cavity perturbation theory and a TM01 cavity. Incorporating the three measured parameters into FEMLAB, we simulated the heating of the sample in the TE102 cavity and compared the simulation with the experimental results.

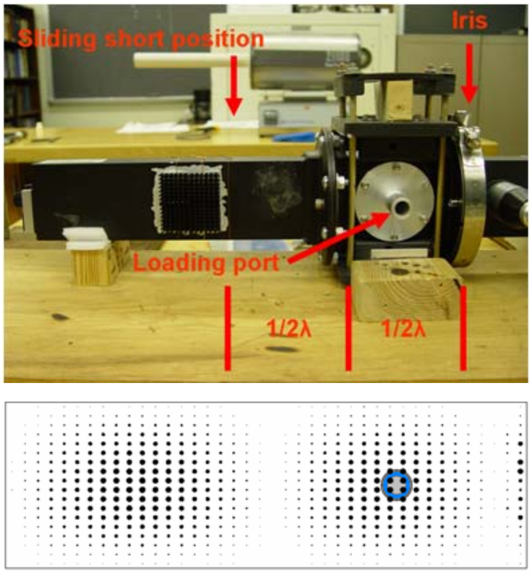
2. Experiments

The 3 micron copper powder provided by Culox Tech Inc. is used in this study. By rigid die pressing, 0.25" (Diameter) by 0.25 inch (Height) cylindrical compacts are prepared. Prior to the compaction, the copper powder is baked in vacuum oven at 120°C for at least 8 hours. No binders or lubricants are used in the process of preparing the samples to avoid possible influence from these agents. A typical 2 tons load is used in the rigid die pressing process and the relative density of the compacts is calculated to be around 72% by comparing the effective density of the compacts to the theoretical density of fully dense copper.

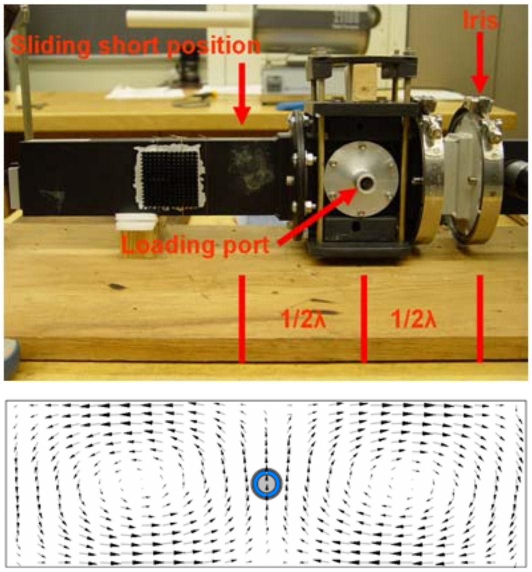
A 1.8kW, 2.45 GHz microwave system provided by Gerling Applied Engineering, Inc. is used to heat the copper compacts. A TE102 single mode cavity consists of a capacitive coupling iris, a half wavelength applicator with two ports, and a sliding short circuit, is constructed as shown in Figure 1. Figure 1a shows the case where the applicator ports are located at the E antinode (in this case, the sliding short circuit is located at the $\lambda_g/2$ distance). By inserting a removable $\lambda_g/4$ straight section waveguide between the applicator and the iris, we effectively shift the applicator ports to the position where E field is zero, (in this case, the sliding short circuit is located at the $\lambda_g/4$ distance). As a result of the two configurations shown in Figure 1, the compacts can be heated in separated E and H fields respectively.

A dual direction coupler and power monitor are used to measure the forward and reverse microwave power. A 3-stub tuner allows for load impedance matching so that we can maintain maximum forward power into the applicator. The temperature of the compacts is measured using an optical non-contact pyrometer provided by Mikron Inc.

Based on perturbation theory, the effective complex permittivity and permeability of the copper compacts are measured using a HP vector network analyzer and a TM01 gold plated cavity as shown in Figure 2. The effective conductivity of the compacts is also measured via the four-point conductivity measurement method.



(a) E field distribution in the TE102 cavity with compacts located at E field antinode



(b) H field distribution in the TE102 cavity with compacts located at E node

Figure 1 The TE102 single mode cavity

Figure 2 The TM01 cavity

3. Theory

Although the mechanism of how the porous metal powder compacts couple with microwave energy and thus heat is still under investigation, it is shown that these compacts show quite dramatically different effective conductivity, permittivity and permeability when compared with those of the corresponding bulk metals. Furthermore, our experiments show that these properties change when a green compact is exposed to microwave and heated for different time periods. Therefore, the heating due to the three aforementioned parameters of the compacts and their change as a function of time should all be considered in this case.

Classical EM theory suggests that the energy conservation over a volume can be expressed as:

$$\oiint (E \times H) ds + \iiint (E \bullet J_t + H \bullet M_t) d\tau = 0$$

This represents in general a conduction term, a displacement term and a source term on the left hand side of the equation. In terms of power supplied to the volume P_s , the power leaving surface bounding the considered volume P_f , the power stored in both electric and magnetic fields $\frac{dW_e}{dt}$ and $\frac{dW_m}{dt}$ respectively, and the power dissipated P_d , this equation can be rewrote as:

$$P_s = P_f + P_d + \frac{dW_e}{dt} + \frac{dW_m}{dt}$$

Now we focus on the dissipated power, which is responsible for the heating of the compacts. If we consider a harmonic microwave field ($E = Ee^{j\omega t}$) as in our experiments, we can derive the expression $\frac{\partial E}{\partial t} = j\omega E$. Together with the generalized definition of the constitutive relation for $D = \left(\varepsilon E + \varepsilon_1 \frac{\partial E}{\partial t} + \varepsilon_2 \frac{\partial^2 E}{\partial t^2} + \dots \right)$, the total induced electric current in the sample can be expressed as:

$$J = [\sigma(\omega) + j\omega\varepsilon(\omega)] E$$

Similarly, we can derive the magnetic current in the sample as:

$$M = j\omega\mu(\omega) H$$

Because the fields are complex due to the harmonic time dependence, the real part of the power flux terms are considered the dissipated power as:

$$P_d = \mathrm{Re}\left\{ \iiint \left\{ \begin{matrix} [\sigma(\omega) + j\omega\varepsilon(\omega)] E^2 \\ + j\omega\mu(\omega) H^2 \end{matrix} \right\} d\tau \right\}$$

If we rewrite the permittivity and permeability in complex form as:

$$\varepsilon = \varepsilon' - j\varepsilon''$$

$$\mu = \mu' - j\mu''$$

Then, the dissipated power can be expressed as:

$$P_d = \mathrm{Re}\left\{ \iiint \left\{ \begin{matrix} [\sigma(\omega) + \omega\varepsilon''] E^2 \\ + \omega\mu'' H^2 \end{matrix} \right\} d\tau \right\}$$

In the COMSOL package, the program only accounted the part of heating due to dielectric loss. Following the above deduction and adding the heating due to magnetic current, the heating source of the compacts can be expressed as the following: (based on the assumption that the compacts have isotropic effective permittivity and effective permeability)

$$Qav\_emw =$$

$$0.5\,\mathrm{Re}\left\{ \begin{matrix} \sigma_{xx} E_x E_x^* + \sigma_{yy} E_y E_y^* + \sigma_{zz} E_z E_z^* \\ - j[\mathrm{Re}(\omega)] E_x D_x^* - j[\mathrm{Re}(\omega)] E_y D_y^* \\ - j[\mathrm{Re}(\omega)] E_z D_z^* - j[\mathrm{Re}(\omega)] H_x B_x^* \\ - j[\mathrm{Re}(\omega)] H_y B_y^* - j[\mathrm{Re}(\omega)] H_z B_z^* \end{matrix} \right\}$$

4. Results

Experiments

Copper powder metal compacts with 3-micron particle size, 72% relative density are subjected to the microwave at both E and H antinodes. The heating behaviors of these compacts in both fields are shown in Figure 3 and Figure 4.

As shown in these graphs, there is an initial sharp rise in temperature that peaks and then relaxes to an equilibrium temperature for both fields (In the case of H field heating, the sample peaks faster and the temperature of the peak reaches at a relatively higher value compared with the E field case). Moreover, the fast temperature rises and peaks occur only in the first heating run of a green compact in both E and H fields heating. Subsequent heating of the same compact after being cooled to room temperature, is characterized by a more gradual and repeatable rise in temperature that reaches the same equilibrium.

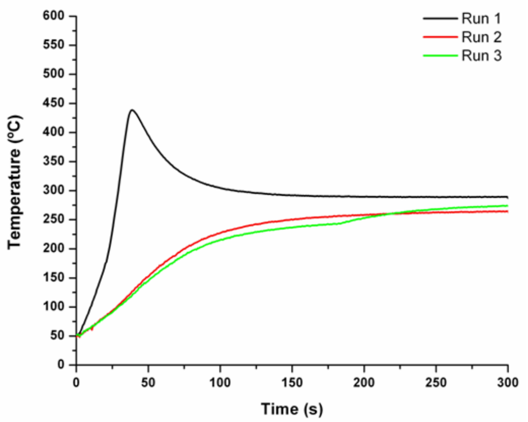


Figure 3 Heating of a 72% dense, 3 micron copper metal powder compact in E field

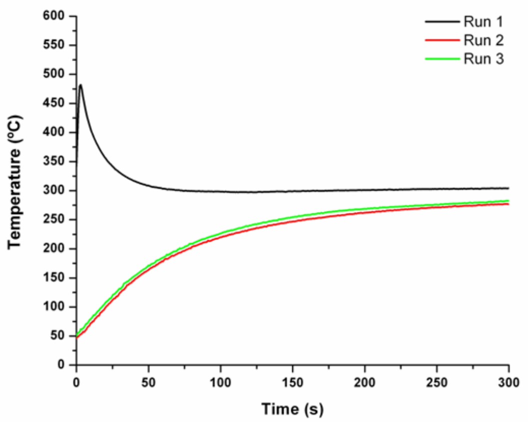


Figure 4 Heating of a 72% dense, 3 micron copper metal powder compact in H field

Simulations

As stated above and shown in the experiments, the effective conductivity, permittivity and permeability of the compacts are not always the same for a green compact and a heated one (Compacts been heated for different time from green status also show different values). These properties change along the heating and thus pre-sintering of the compacts. Therefore, we conducted a series of experiments to heat 'identical' compacts (compacts with the same dimension and relative density) for different time intervals. Then, the three parameters of these compacts are measured and used in the simulation of heating of green compacts. For the subsequent heating of these compacts, constant values are used. Figure 5, Figure 6 and Figure 7 shows the measured evolution of the three parameters for copper compacts heated in E and H fields for various time periods.

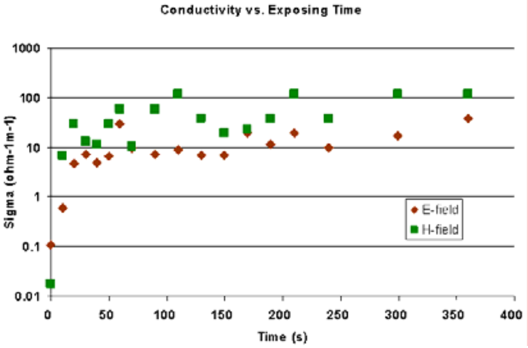


Figure 5 Conductivity of the compacts as a function of time

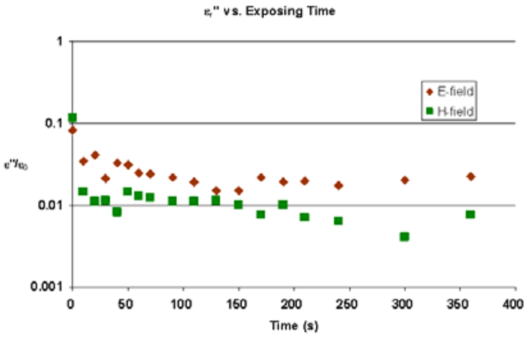


Figure 6 Imaginary part of the complex permittivity as a function of time

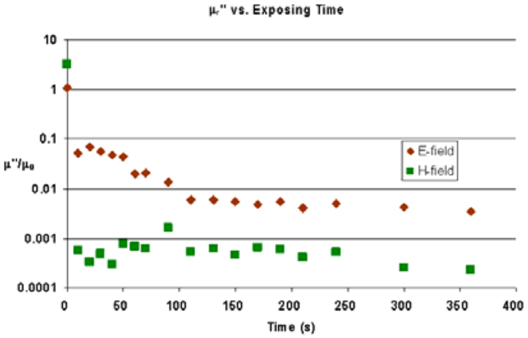


Figure 7 Imaginary part of the complex permeability as a function of time

Figure 8 and Figure 9 show the comparison of the experimental heating results to the simulation ones for both E and H field cases. As one can see, they show an acceptable agreement with each others in both E and H fields heating.

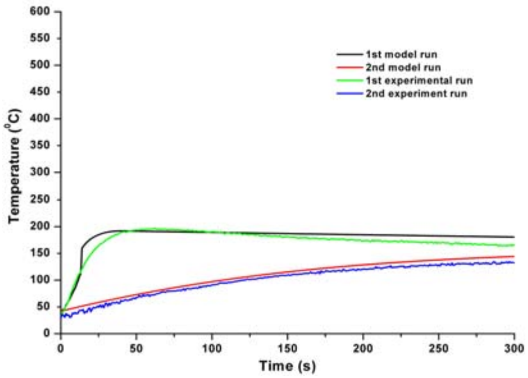


Figure 8 Experimental and simulation results for the E field heating

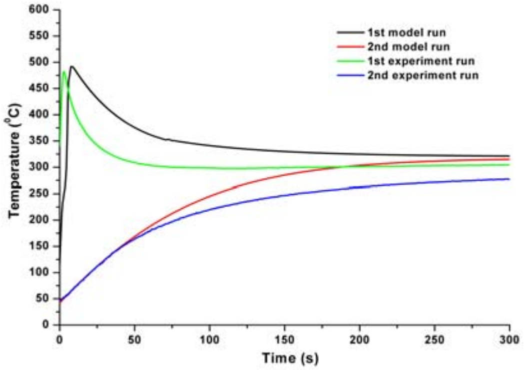


Figure 9 Experimental and simulation results for the E field heating

5. Conclusions

According to our results, we concluded that other than effective conductivity and permittivity, effective permeability of the compacts should also be considered in the case of simulating coupling and therefore heating of metal powder compacts subjected to microwave irradiation. For a green compact, its effective conductivity, permittivity and permeability change and there is a rapidly reached temperature peak when heated for the first time. After a certain period of time, when the temperature of the compact reaches equilibrium, its three parameters stay constant. Subsequent heating of a heated compact shows no temperature peak rather than a gradual increase to the same equilibrium temperature as the heating of a green compact.

Using the measured values of the parameters for the compacts and including contribution of effective permeability, a good agreement between simulation results and the experimental ones is observed.

6. Acknowledgements

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