§15. Numerical Simulation of the Microwave Heating of Copper Powders in a Single Mode Cavity

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Recently the expression for the estimation of effective parameters of compacted powdered metals has been obtained by means of the combination of Mie theory and Bruggeman's effective medium[1]. For example, in this approach the effective permeability $\mu_{\rm eff}$ is determined by solving the equations

$$p\frac{\mu_{\rm p}-\mu_{\rm eff}}{\mu_{\rm p}+2\mu_{\rm eff}}+(1-p)\frac{\mu_{\rm g}-\mu_{\rm eff}}{\mu_{\rm g}+2\mu_{\rm eff}}=0, \tag{1}$$

where p is the volume fraction of particles; the permeability $\mu_{\rm g}$ is the optical parameters of gas in pores; and

$$\mu_{\rm p}=2\mu_2\frac{1-(r_1/r_2)^3\beta_a}{2+(r_1/r_2)^3\beta_a},\ \beta_a=2\frac{1-(\mu_1/\mu_2)F_1}{2+(\mu_1/\mu_2)F_1}. \tag{2}$$

Here, $r_{1,2}$ are the radii of the metal core and the insulating shell; $\varepsilon_{1,2}$ and $\mu_{1,2}$ are the permittivity and permeability of the core and the shell, respectively. The factor F_1 is

$$F_1(y)=2\frac{-y\cos y+\sin y}{y\cos y-\sin y+y^2\sin y}, \tag{3}$$

with $y\equiv k_1r_1$, where $k_{1,2}=\omega\sqrt{\varepsilon_{1,2}\mu_{1,2}}$, $\omega=2\pi f$, f is the frequency of the incident wave.

The estimated parameters of copper powders are shown in Table I. By means of the obtained parameters, the numerical simulation of the microwave heating of a spherical sample is performed. Radius of the sample is 5 mm. Results of the calculations are shown in Fig. 1. When the sample is placed in the free-space standing wave, it is well heated by the H-field but not by the E-field component of the microwaves. Clearly, the external electric field is perfectly screened out by conduction electrons in metals, and therefore it cannot heat the copper powders. In contrast, the magnetic field still penetrates by the skin-depth deep, and when the particle size in the powder is small, as in the presented case, the dissipation of the microwave energy due to Joule loss is strong enough to heat the powders.[2]

The situation is different when the sample in the sample holder is placed in a single mode cavity. Parameters of the cavity are corresponded to those shown in the paper of Ma *et al.*[3] Intensity of the E-field is the same as in the free-space standing wave. In this case, heating rate in the E-field maximum is enhanced while that in the H-field maximum is almost the same as in previous calculations. Now, in some situations the sample is still heated in the H-field maximum much stronger than in the E-field one (Fig. 1(a)). At the same time, it is also possible the situation, when heating in the E-field maxim is stronger than that in the H-field (Fig. 1(b)).

The free-space results suggest that the enhancement of heating in the E-field maximum is associated with the imperfect separation of the E-field and H-field components in the cavity. It means that experiments utilizing separation of E and H-fields need to be performed carefully.

Table I: Parameters of the copper powders used in calculations (r_2-r_1 = 50nm, p=0.5, f=2.45GHz, $\varepsilon/\varepsilon_0 = 5+i0.5$, T= 27^{0}C).

$r_{\rm particle}$ [μm]	1	10
$\varepsilon_{\rm eff}/\varepsilon_0$	$27+i2.7$	$252+i25.2$
$\mu_{\rm eff}/\mu_0$	$0.99+i0.05$	$0.46+i0.12$
$K_{\rm eff}$ [W/K m]	43.3	93

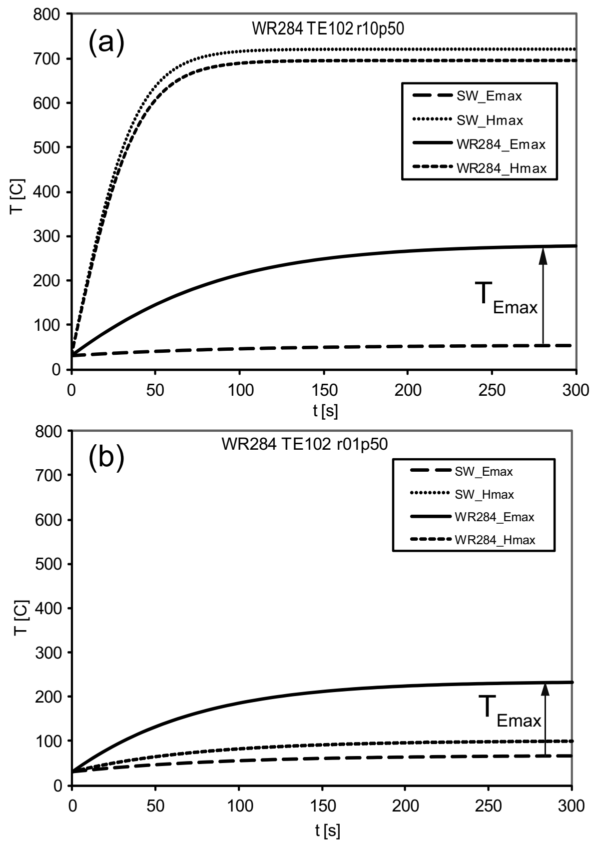

Fig. 1: Calculated heating history for the sample made of (a) 10 μm and (b) 1 μm particles. Here, SW stands for free-space standing wave, WR284 indicate the heating in the single mode cavity.

1) M. Ignatenko and M. Tanaka: Physica B **405** (2010) 352

2) M. Ignatenko, M. Tanaka and M. Sato: Jpn. J. Appl. Phys. **48** (2009) 067001

3) J. Ma, J. F. Diehl, E. J. Johnson *etc*: J. Appl. Phys. **101** (2007) 074906.