§21. Estimation of the Effective Permittivity and Permeability of Metal Powders at Microwave Frequencies

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Recent developments of the microwave heating of compacted metal powders bring a demand on calculation of corresponding effective optical parameters. Since the existing models cannot be applied to such powders, we developed new effective dielectric permittivity and magnetic permeability by means of the combination of Mie theory and Bruggeman's effective medium. In this approach, the effective permittivity $\varepsilon_{\rm eff}$ is determined by solving the equation

$$p\frac{\varepsilon_{\rm p}-\varepsilon_{\rm eff}}{\varepsilon_{\rm p}+2\varepsilon_{\rm eff}}+(1-p)\frac{\varepsilon_{\rm g}-\varepsilon_{\rm eff}}{\varepsilon_{\rm g}+2\varepsilon_{\rm eff}}=0. \quad (1)$$

where p is the volume fraction of particles; $\varepsilon_{\rm g}$ is the permittivity of gas in pores; and

$$\varepsilon_{\rm p}=\varepsilon_2 F_2^b, \quad (2)$$

$$F_2^b=2\frac{1-(r_1/r_2)^3\beta_b}{2+(r_1/r_2)^3\beta_b},\ \beta_b=2\frac{1-(\varepsilon_1/\varepsilon_2)F_1}{2+(\varepsilon_1/\varepsilon_2)F_1}. \quad (3)$$

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

$$F_1(y)=2\frac{-y\cos y+\sin y}{y\cos y-\sin y+y^2\sin y}, \quad (4)$$

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. For highly conducting nonmagnetic materials $k_1r_1=(1+i)r_1/\delta$, where $\delta=\sqrt{2/\omega\sigma\mu_0}$ is the skin depth ($\mu_0=1.2566\times10^{-6}$ H/m is the permeability of free space, σ is the static conductivity).

The effective permeability $\mu_{\rm eff}$ can be found from Eqs. (1)-(4) by replacing ε with μ.

Effect of the insulating shell. In microwave heating experiments, the radius of metal core r_1 is frequently much larger than the thickness of shells, i.e. $\Delta r\equiv r_2-r_1\ll r_1$, which raises a question of the influence of the shell on the effective parameters. Nevertheless, the calculations show that even a very thin shell $\Delta r/r_1<1\times10^{-2}$ significantly reduces $\varepsilon_{\rm eff}$ in comparison with the permittivity of the core (Fig. 1).

Magnetic properties of nonmagnetic powders. When an nonmagnetic metal particle ($\mu_1=\mu_2=\mu_0$) is subjected to microwave irradiation, an induced current causes magnetic moment and the particle effectively behaves like a magnetic one (Fig. 2). The result shows that the particles do not couple with the magnetic component when the grain cores are very small ($\mu_{\rm p}\to\mu_0$ when $r_1/\delta\ll1$) or very large ($\mu_{\rm p}\to0$ when $r_1/\delta\gg1$). Between these cases, there is a region where the imaginary part of the "permeability of grain" $\mu''_{\rm p}$ has a maximum. The flow of the induced current changes here from volumetric to surface one[1, 2].

The obtained expressions provide theoretical support for microwave heating of metal powders.

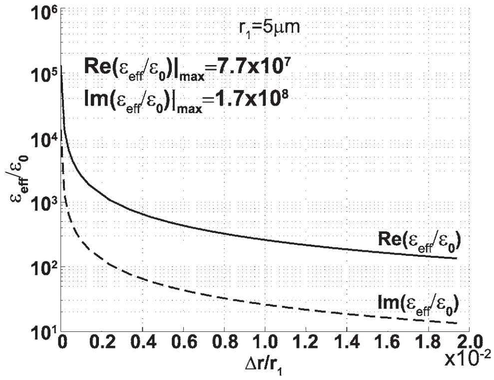

Fig. 1: Effect of the shell thickness on effective permittivity $\varepsilon_{\rm eff}$ for $\varepsilon_2/\varepsilon_0=3+i0.3$, $r_1=5\,\mu$m, $p=0.9$, $\sigma=5.8\times10^7$ S/m and $f=2.45$ GHz. The shell thickness Δr changes from 0.1 nm to 100 nm. The results demonstrate that even a thin shell drastically reduces $\varepsilon_{\rm eff}$.

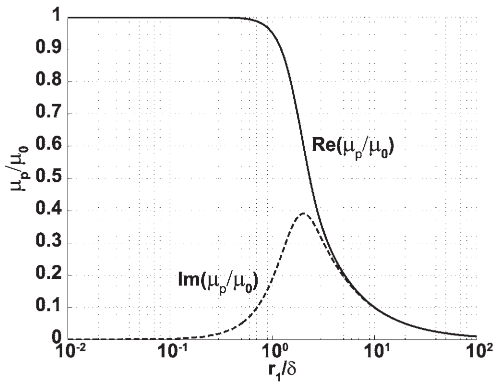

Fig. 2: The induced "permeability of grain" $\mu_{\rm p}$ in the case of nonmagnetic homogeneous particle as a function of r_1/δ ratio. The result demonstrates that in spite of nonmagnetic material, the grains themselves show magnetic behavior.

1) L. D. Landau, E. M. Lifshits, and L. P. Pitaevskii: *Electrodynamics of Continuous Media* (Pergamon, Oxford, 1984) 2nd ed., p. 201.

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