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Numerical Study of Microwave Heating of Micrometer Size Metal Particles

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Absorption of microwave energy in conductive nonmagnetic spherical particles is analyzed by means of finite element method. The frequency of the microwave is 2.45 GHz. To find out roles of the electric and magnetic fields in the heating process, conditions of the electric and magnetic anti-nodes in a standing wave are simulated. Results clearly show that single metallic particles are mostly heated by the magnetic component of the electromagnetic field. Density of the absorbed energy has maximum at some fixed particle radius, which equals to 3.3 μm for the case of copper particles. Penetration length into multi particle system is estimated.

KEY WORDS: microwave heating and sintering; powdered metals; finite element method; Joule loss; Mie theory.

1. Introduction

Nowadays, microwaves are typically used for food cooking. However, they are also utilized in industry to process absorbing materials like ceramics, evaporate water *etc.* Recently, this technique has been extended to electrically conducting powders.[1–3] In contrast to conventional methods, microwaves can transport energy inside the samples, producing volumetric heating; time of sintering sufficiently reduces, and properties of final product are at least as good as those sintered conventionally or even better. For example, the use of microwaves substantially simplifies and accelerates production of steel.[4,5]

In the case of bulk metals, the alternating electromagnetic waves can effectively penetrate inside a conductive body only by the skin depth. The skin depth $\delta=\sqrt{2/(\sigma\omega\mu)}$ is determined by the wave angular frequency ω, the body conductivity σ and magnetic permeability μ. For highly conductive materials the skin depth at microwave frequencies is very small. For example, in the present study the particles are irradiated by microwaves with frequency $f=2.45$ GHz, therefore the skin depth of copper [$\sigma=5.8\times10^7$ S/m (see, for example, Ref. 6)] is $\delta\approx1.33$ μm. As a result, a macroscopic body made from bulk metal can not be effectively heated by microwaves. The situation differs in the case of compacts of powdered metals. In this case, the effective skin depth can reach a few centimeters,[7] making possible deep penetration of microwaves in compacts of powdered metals and subsequent volumetric heating.

In this paper, microwave heating of highly conducting nonmagnetic particles is analyzed. To find out roles of the electric and the magnetic components of the electromagnetic field in the heating process, a standing wave conditions are simulated. Penetration of microwaves in semi-infinite system of metallic cubic particles is roughly estimated.

2. Numerical Model

In the present study, the JMAG-Studio software ver.8.41301y (JRI solutions, Limited) is used for calculations.[8] In order to find out roles of the electric and magnetic components of the electromagnetic field, particles are placed either in the electric or magnetic anti-nodes of standing wave or it is irradiated by traveling wave.

During the numerical analysis, source produces a plane z-polarized wave propagating in x-direction. It heats a single copper particle or semi-infinite plate composed of the copper particles. Typical radius of the particles R lies within 1–10 μm range. Thus, the particles sizes are much less than the wavelength of microwaves, but they are comparable with the skin depth. The particles are surrounded by free space.

The JMAG-Studio software provides a number of boundary conditions. In the calculations, to maintain the polarization state, perfect electric conductor (PEC) conditions at the top and bottom of the simulation box along with perfect magnetic conductor (PMC) conditions at the left and right sides of the box are applied (**Fig. 1**). The front side is the source plane. The flow of input energy is 10^4 J/(m^2 s). The boundary condition applied to the back side depends on the aim of simulation. If irradiation of a particle by traveling electromagnetic wave (case EM) is considered, then absorb-

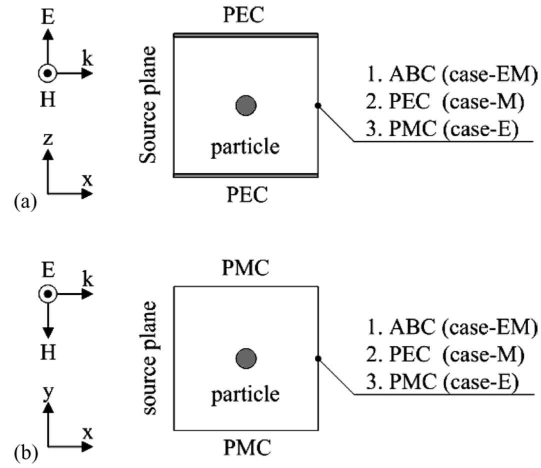

Fig. 1. Scheme of the numerical model. A single metal sphere is placed between the pair of parallel PEC and PMC plates normal to the *z* and *y*-axes, respectively; sideview of (a) *x–z* plane and (b) *x–y* plane. Microwaves propagate in the *x* direction.

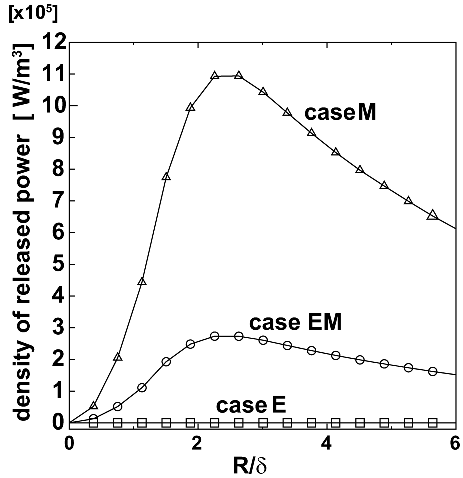

Fig. 2. The density of the released power as the function of the R/δ parameter, for three different boundary conditions: case E, case M and case EM., where R is the particle radius and δ is the skin depth.

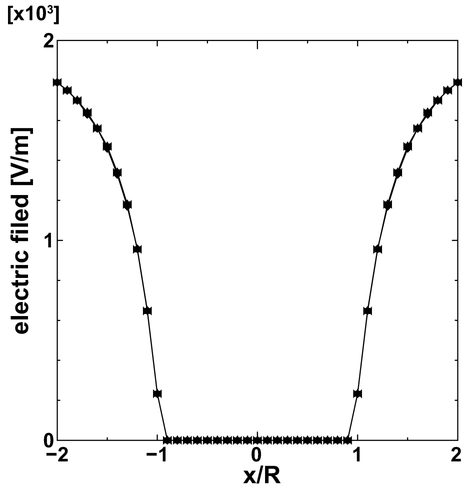

Fig. 3. Distribution of the electric field along the *x*-axis on the equatorial plane. The origin is set at the particle center. The particle is irradiated by plane traveling waves. The electric field inside the particle is always suppressed. In the shown scale, shape of the electric field distribution does not depend on the particle radius R.

ing boundary condition (ABC) is applied. Other choices are to use the PEC boundary condition to simulate a sample heating in the maximum of the magnetic field of a standing wave (case M), and the PMC boundary condition to analyze heating in the maximum of the electric field (case E).

Tetrahedral meshes have been examined to provide accurate results even with relatively sparse grid and they are used for the single particle calculations. The mesh size is equal to $R/10$.

In the multi-particle case, side PEC and PMC boundaries are replaced by periodic boundary conditions, and thus the conditions of a semi-infinite plate composed of the metal particles are reproduced. To reduce time of calculation and due to limited PC resources, a uniform cubic mesh is used. The size of cell is 1 μm. This cell size is less than the skin depth, and it can be used for the rough estimation of the penetration length.

3. Results of Simulation

3.1. Heating of the Single Particle

In the beginning, heating of the single copper spherical particle in traveling and standing waves is analyzed.

The density of the released power is shown in **Fig. 2**. The results demonstrate that the particle is the most effectively heated in the magnetic field maximum of the standing wave. The power released in the particle in the traveling wave is four times less than that in the magnetic field anti-node. When the particle is placed in the electric field anti-node, it releases negligible amount of power.

In the absence of magnetic losses, heating of electrically conductive material is always caused by the Joule loss mechanism. The current is generated by the electric field, which in turn can be induced by alternating magnetic field. Different amounts of the released power density suggest different amplitudes of the current density and, correspondingly, different amplitudes of the internal electric field. Indeed, in the high conductive particle, the external electric field is effectively suppressed, even when the particle is smaller than the skin depth, making heating in the electric field anti-node inefficient (**Fig. 3**). It is supported by the fact that at microwave frequencies the intrinsic impedance of good conductors is much less than the impedance of free space $\eta_0=376.73$ Om. The impedance η shows ratio of the electric (E_0) to the magnetic field (H_0) amplitudes and it is equal to[9)]

$$\eta \equiv \frac{E_0}{H_0} = \sqrt{\frac{\mu}{\varepsilon}} \quad \text{..........................(3.1)}$$

where, ε is the electrical permittivity and μ is the magnetic permeability. For example, in the case of harmonic incident wave, it is possible to introduce effective permittivity as $\varepsilon=(\varepsilon_r+i\sigma/\omega\varepsilon_0)\ \varepsilon_0$, where ε_r is the relative electrical permittivity and $\varepsilon_0=8.854\times10^{-12}$ F/m is the permittivity of free space (see, for example, Ref. 10)). For the modeled conditions, permittivity of copper is $\varepsilon\approx(1+i4.29\times10^8)\varepsilon_0$ and its permeability equals to permeability of free space, therefore $|\eta|\approx4.82\times10^{-5}\eta_0$, *i.e.* internal electric field

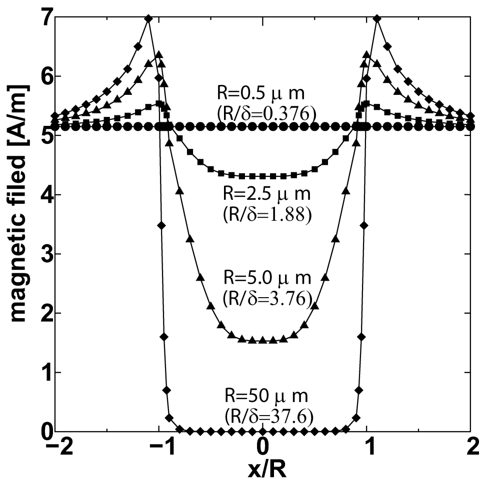

Fig. 4. Distributions of the magnetic field along the x-axis on the equatorial plane. The origin is set at the particle center. The particle is irradiated by plane traveling waves. Note, when $R<\delta$ ($R=0.5\,\mu$m), the magnetic field is only slightly disturbed. Here, R is the particle radius and δ is the skin depth.

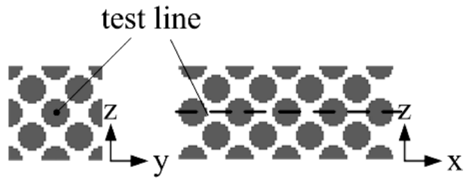

Fig. 5. The configuration of metal particles arranged in body-centered cubic lattice sites. The particle radius is $R=6\,\mu$m, the distance between centers of adjacent particles is 20 μm. Data are sampled along the test line.

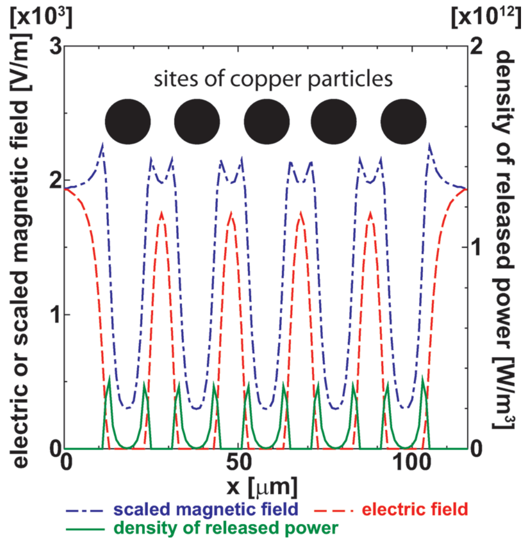

Fig. 6. The amplitudes of the electric and magnetic fields and density of the released energy along the test line shown in Fig. 5. Dashed (red) and dot-dashed (blue) lines represent the electric and magnetic fields, respectively, and the solid line (green) shows the density of released energy. The magnetic field is scaled as $\eta_0 H$ ($\eta_0=376.73\,\Omega$).

within the skin depth is suppressed approximately by 4–5 orders of magnitude compared to the external one under the assumption of unperturbed magnetic field.

When the particle is in the magnetic field maximum, the amplitude of the magnetic field within the skin depth is of the same order as that of the external field (**Fig. 4**, $x/R\approx 1$). In this case, internal electric field is highly suppressed in comparison with the external one, but it is still enough for heating (Fig. 2, case M). Placing the particle in the electric field anti-node, internal magnetic field becomes much smaller, inducing even smaller internal electric field. As a result, the particle releases negligible amount of energy (Fig. 2, case E). Therefore, high conductive particles are most effectively heated in the magnetic field.

Heating in the traveling wave can be considered as a superposition of heating in the electric and in the magnetic fields. Since contribution from the electric field is much less than that from the magnetic field, the power released by the particle in a traveling wave is exactly four times less than that released in the magnetic maximum (Fig. 2, case EM). Here, it is necessary to take into account that the amplitudes of the electric and magnetic fields in the traveling wave is twice smaller than those of corresponding maxima of the standing wave.

The simulation shows that the density of released power has maximum at some intermediate particle size (Fig. 2). The position of this maximum expressed in terms of the skin depth is located at $R_m\approx 2.5\delta$. For the case of copper, $R_m\approx 3.33\,\mu$m.

3.2. Estimation of Penetration Depth in Multi Particle System

In this section, penetration of microwaves into multi particle systems is considered. The metal particles are arranged into regular body-centered cubic lattice. Size of the particles is 6 μm. Distance between the particles is 20 μm. Samples are heated by traveling wave. The configuration of metal particles is shown in **Fig. 5**.

Here, the penetration scale length is estimated for a low density sample. The density of the multi particle system is 17%. The empty space is filled by air, and such a system can be considered as filled with nonabsorbing and nonconducting medium. Dimensions of the simulated part of the semi-infinite system are $92\times 40\times 40\,\mu$m^3.

The penetration scale length is estimated as

$$L_\delta=\frac{2I_0}{\left|\dfrac{dI}{dl}\right|} \quad\text{..............................(3.2)}$$

where I_0 is the incident energy flux, gradient dI/dl is taken perpendicularly to boundary, and the depth is estimated at the sample edge. For the case of bulk metal, the energy flux changes as $I(l)=I_0\exp(-2l/\delta)$ due to the skin effect, therefore $L_\delta=\delta$.

The amplitudes of the electric and magnetic fields, and density of the released energy along the test line are shown in **Fig. 6**. Clearly, the electromagnetic wave passes through the simulated system only with slight attenuation. The ratio of absorbed energy to incident one is 3.8×10^{-4}, and from Eq. (3.2) the penetration scale length is roughly $L_\delta\approx 0.48$ m. This example demonstrates, that at least in the case of a low density sample, the penetration depth can exceed the skin depth by 4–5 orders, allowing volumetric heating.

4. Conclusions

Numerical analysis of microwave heating of the single nonmagnetic metal particle and that of the multi particle system are performed by the JMAG-Studio software.

Our simulation confirms that due to high conductivity of metal particles, the electric field is highly suppressed inside of them even if the particle radius is less than the skin depth. For this reason, the pure metal particles are most effectively heated by the magnetic component of the electromagnetic field.

The results show, that density of the released energy has maximum within modeled range of the particles radii. For copper particle the maximum occurs when the particle radius is approximately 3.3 μm.

The possibility of deep penetration of the electromagnetic wave inside the compacts of powdered metals is demonstrated by the example of a low density semi-infinite plate composed of copper particles. The density of the plate is 17%. The penetration scale length is estimated to be 0.48 m allowing volumetric heating.

For the present multi particle calculations, rough mesh is used because of limited PC resources. For more accurate estimations of the penetration scale length, the mesh should be refined. Another question is that the considered multi particle system has low density, while typical density of powdered metal compacts is much higher. It seems that the density influences the microwave penetrating into the metallic powder compacts.[11] The clarification of the relations between the density of the compacts and the loss of the electromagnetic wave will be performed in near future.

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REFERENCES

1) R. Roy, D. Agrawal, J. Cheng and S. Gedevanishvili: *Nature* (*London*), **399** (1999), 199.
2) J. Cheng, R. Roy and D. Agrawal: *J. Mater. Sci. Lett.*, **20** (2001), 1561.
3) S. Takayama, Y. Saito, M. Sato, T. Nagasaka, T. Muroga and Y. Ninomiya: *Jpn. J. Appl. Phys.*, **45** (2006), 1816.
4) K. Ishizaki and K. Nagata: *ISIJ Int*., **47** (2007), 811.
5) K. Ishizaki, K. Nagata and T. Hayashi: *ISIJ Int*., **47** (2007), 817.
6) D. R. Lide (ed.): CRC Handbook of Chemistry and Physics, 86th ed., CRC Press, New York, (2005), 12.
7) J. Ma, J. F. Diehl, E. J. Johnson, K. R. Martin, N. M. Miskovsky, C. T. Smith, G. J. Weisel, B. L. Weiss and D. T. Zimmerman: *J. Appl. Phys.*, **101** (2007), 074906.
8) http://www.jri.co.jp/pro-eng/jnag/index.html (Access: 2008/3/31)
9) J. A. Stratton: Electromagnetic Theory, McGraw-Hill, New York, (1941), 283.
10) C. F. Bohren and D. R. Huffman: Absorption and Scattering of Light by Small Particles, John Wiley & Sons, Inc, New York, (1983), 15.
11) S. Takayama, G. Link, S. Miksch, M. Sato, J. Ichikawa and M. Thumm: *Powder Metall,*, **49** (2006), 274.