MICROWAVE HEATING OF CONDUCTIVE MATERIALS

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In recent years a considerable interest has been drawn to microwave heating of powder metals and other conductive materials. This presentation reviews some fundamental concepts that determine absorption of energy from electromagnetic waves in conductive materials with different dielectric and magnetic properties.

In a dc electric field the local density of the energy released at any point of the material can be expressed as $w = \sigma \mathbf{E}^2$, where $\mathbf{E}$ is the vector of electric field at this point and σ is a material property called electric conductivity. For alternating field, such as that in an electromagnetic wave, the effective electric conductivity is introduced that accounts for all electric-type losses in the material and is related to the imaginary part of its dielectric permittivity, ε'', as $\sigma = \varepsilon''\omega / 4\pi$, where ω is the field frequency. In addition, some materials exhibit magnetic-type energy losses in such processes as reorientation of magnetic domains. In general, the total energy released in a material in alternating electric and magnetic fields is expressed as $w = \omega / 4\pi\ (\varepsilon''\mathbf{E}^2 + \mu''\mathbf{H}^2)$, where μ'' is the imaginary part of magnetic permeability, and $\mathbf{H}$ is the magnetic field vector.

In the most common applicators a standing electromagnetic wave is usually present, and the maxima of the electric and magnetic field are separated in space. Therefore, the heating of a small sample is dependent on its spatial position. If the sample has low losses ($\varepsilon'' \ll 1$, $\mu'' \ll 1$), the optimum position for heating can be determined by comparing the values of electric ($\sim \varepsilon''\mathbf{E}^2$) and magnetic ($\sim \mu''\mathbf{H}^2$) losses, using the unperturbed field values $\mathbf{E}$ and $\mathbf{H}$. In particular, for most materials $\mu'' = 0$ and the optimum heating occurs in the maximum of electric field.

However, in conductive materials with the electric type of losses ($\varepsilon'' \gg 1$, $\mu'' = 0$) the external electric field may be suppressed inside the sample even when its dimensions are smaller than the skin depth, i.e., when the magnetic field is only slightly perturbed. Therefore the heating of such conductive materials may be more efficient when the sample is placed in the maximum of magnetic field (inductive heating). The heating in this case remains "electric" in nature; however, the rotational electric field causing it is generated in the conductive material due to the alternating magnetic field. The optimum position for heating can generally be determined by solving Maxwell equations and obtaining the perturbed fields inside the sample.

The solutions of electromagnetic problems are considered for two cases. In the first case, a small spherical sample with both electric and magnetic losses ($\varepsilon'' \neq 0$, $\mu'' \neq 0$) is considered in uniform external fields $\mathbf{E}$ and $\mathbf{H}$. The radius of the sample is assumed to be less than the skin depth and less than the vacuum wavelength corresponding to the field frequency. The total absorbed power in such a sample consists of three additive terms: dielectric losses ($\sim \mathbf{E}^2$) whose dependence on ε'' is non-monotonous with a maximum, inductive heating ($\sim \varepsilon''\mathbf{H}^2$), and magnetic losses ($\sim \mu''\mathbf{H}^2$). The power absorbed due to inductive heating has a different dependence on the radius of the sample ($\sim R^5$) compared to other terms ($\sim R^3$). Therefore, the optimum position for heating depends also on the dimensions of the sample.

In the second case, a small (radius less than the wavelength in vacuum) spherical sample with no magnetic losses ($\varepsilon'' \neq 0$, $\mu'' = 0$) is considered in a standing plane electromagnetic wave. The total absorbed power is calculated for the sample positioned in the maximum of electric or in the maximum of magnetic field in the standing wave. It is shown that the inductive term in the absorbed power has a non-monotonous dependence on ε'' and reaches its maximum when the radius of the sample is on the order of the skin depth.

The conditions for thermal runaway development are reviewed for the cases considered. In particular, it is shown that when $\varepsilon'' \gg 1$, a thermal runaway is possible only in the maximum of magnetic field.

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