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Absorption characteristics of single-layer ceramics under oblique incident microwave irradiation

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Abstract

The absorption characteristics of single-layer ceramics under oblique incident microwave irradiation were investigated by evaluating the effect of microwave incident angle (θ_i) on reflection losses (*RL*) for both transverse electric (TE) and transverse magnetic (TM) polarizations. The materials investigated were a high-loss SiC layer and a low-loss Al_2O_3 layer with impedance matching thicknesses of 0.0054 and 0.923 m, respectively. The reflection losses of the ceramic layers over the incident angle ranging from 0° to 90° were determined using equations derived from transmission line theory. From the *RL* patterns obtained, SiC exhibits a much smaller minimum reflection loss (RL_{min}) at a higher θ_i for TM polarization compared with the equivalent for TE polarization. This difference is believed to be a result of the effect of Brewster's angle. For Al_2O_3 at room temperature, there is a negligible difference of RL_{min} between TE and TM polarizations due to the low dielectric loss of Al_2O_3. When temperature increases to 1379 °C, the Al_2O_3 RL_{min} values for TE polarization show frequent fluctuations in the entire temperature range, indicating the difficulty in predicting absorption in low-loss materials for TE polarization during microwave heating. For TM polarization, reflection loss of Al_2O_3 varies monotonically with θ_i as the temperature is increased that is shown by a decreasing RL_{min} value when the corresponding incident angle increases. These results indicate that TM-polarized microwaves help reduce reflection losses of both high- and low-loss ceramics. Power absorption in ceramics throughout the heating process can be improved by modifying the angle of incidence and polarization type of microwaves.

Keywords: A. Microwave processing; D. Al_2O_3; D. SiC; Oblique incidence; Polarization

1. Introduction

Microwave processing of both high-loss and low-loss ceramic materials (e.g., SiC and Al_2O_3) has raised extensive interest from the academic community due to some major advantages of microwave heating [1–8]. Because this technology features volumetric and selective heating which relies on microwave–material interactions, microwave propagation/dissipation behaviours and microwave absorption properties of materials play important roles in processing. Many efforts have been taken to achieve maximum microwave absorption which determines the success of a heating process, such as optimization of material dimension and application of variable frequency microwave radiation [9–13]. Instead of performing extensive experimental work in an effort to improve microwave heating, further theoretical research is required to identify characteristics of microwave absorption in materials [13,14].

Recent work indicates that reflection loss (*RL*) analysis is helpful in the design of absorbers for microwave heating by simultaneously considering the effects of multiple factors

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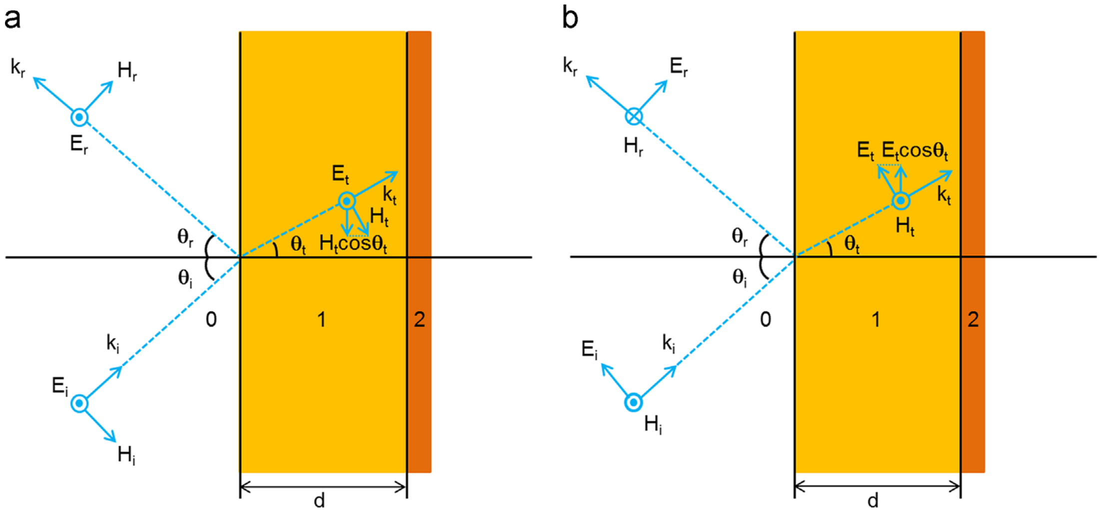

Fig. 1. Schematic of TE and TM polarizations in which incident, transmitted, and reflected electric and magnetic fields components of microwaves are denoted by *E* and *H* with subscripts, *i*, *t* and *r*, respectively. The direction of microwave propagation is represented by *k* and media, including air, absorber and metal (microwave cavity wall), are denoted by numbers 0, 1 and 2, respectively.

(permittivity, permeability, absorber thickness, microwave frequency, etc.) that influence microwave power absorbed in the materials [15]. Absorber thickness can be optimized when impedance matching is achieved by minimizing reflection loss ($RL \rightarrow -\infty$) [16]. With this condition, a considerable increase in absorption is achieved in the materials having the matching thickness. Nevertheless, these results were obtained when the incident microwaves were perpendicular to the sample surface. Because it is sometimes difficult to ensure or control the incident angle of microwaves in a specified cavity during materials processing, a detailed examination of the effect of oblique (non-perpendicular) incident microwave irradiation on microwave absorption in materials is required. Such examination is especially important for microwave processing of ceramics, which should maximize microwave absorption in a wide temperature range. To date, however, no effort has been made to characterize microwave absorption in ceramics under oblique incident microwave irradiation throughout the heating process based on reflection loss analysis.

The present work is aimed at achieving the maximum microwave absorption in single-layer ceramic absorbers under oblique incident microwave irradiation by studying reflection losses of a high-loss SiC layer and a low-loss Al_2O_3 layer over a wide incident angle (θ_i) range for TE and TM polarizations. The characteristics of microwave absorption in the ceramics at temperatures up to 1379 °C were determined using *RL* formulas derived from transmission line theory. The results reveal that microwave absorption in both low- and high-loss ceramics throughout the heating process can be enhanced by modifying the angle of incidence and polarization type of microwaves.

2. Reflection losses for TE and TM polarizations

The microwave reflection loss of a material depends on various factors, including microwave permittivity, permeability, microwave frequency and material thickness. The traditional formula for determining reflection loss of a single-layer microwave absorber backed by a metallic cavity wall under microwave irradiation (perpendicular incidence, $\theta_i=0$) has been widely reported as follows [17]:

$$RL(TEM) = 20\log\left|\frac{\sqrt{\mu_r/\varepsilon_r}\tanh\left(j\frac{2\pi f}{c}\sqrt{\varepsilon_r\mu_r}d\right)-1}{\sqrt{\mu_r/\varepsilon_r}\tanh\left(j\frac{2\pi f}{c}\sqrt{\varepsilon_r\mu_r}d\right)+1}\right|, \qquad (1)$$

where j is the imaginary unit, f is the microwave frequency, c is the speed of light, μ_r and ε_r are, respectively, the complex relative permeability ($\mu_r=\mu_r'-j\mu_r''$) and permittivity ($\varepsilon_r=\varepsilon_r'-j\varepsilon_r''$) of the given absorber which include real (μ_r', ε_r') and imaginary parts (μ_r'', ε_r''), and d is the absorber thickness.

For an oblique incidence of microwaves (plane waves), the incident angle influences reflection and refraction of microwaves on the interface between air and the absorber so both TE and TM polarizations should be considered. Fig. 1 shows a schematic of incidence of TE- and TM-polarized microwaves. The characteristic impedance (Z_c) of the absorber for TE and TM polarizations and input impedance of microwaves (Z_{in}), which are directly associated with the refraction angle (θ_t), are given by [18]

$$Z_c(TE) = \frac{E_t}{H_t\cos\theta_t} = \frac{\sqrt{\mu/\varepsilon}}{\cos\theta_t} = \frac{\sqrt{\mu_r\mu_0/\varepsilon_r\varepsilon_0}}{\cos\theta_t} = \frac{\eta_0\sqrt{\mu_r/\varepsilon_r}}{\cos\theta_t}, \qquad (2)$$

$$Z_c(TM) = \frac{E_t\cos\theta_t}{H_t} = \sqrt{\mu/\varepsilon}\cos\theta_t = \sqrt{\mu_r\mu_0/\varepsilon_r\varepsilon_0}\cos\theta_t = \eta_0\sqrt{\mu_r/\varepsilon_r}\cos\theta_t, \qquad (3)$$

$$Z_{in} = Z_c\tanh\left(j\frac{2\pi f}{c}\sqrt{\varepsilon_r\mu_r}\cos\theta_t d\right), \qquad (4)$$

where μ and ε are the permeability and permittivity of the absorber, respectively, μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ H/m),