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 range from 0 to 90° were determined using the 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, shown by a decreasing RL_{min} value when the corresponding incident angle increases. These results indicate that TM-polarized microwaves help to 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: Microwave processing; SiC; Al_2O_3 ; Oblique incidence; Polarization

1. Introduction

Microwave processing of both high-loss and low-loss ceramic materials (e.g., SiC and Al₂O₃) 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 rely on microwave-material interactions, microwave propagation/dissipation behaviors 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 (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 Al₂O₃ 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]:

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

where j is the imaginary unit, f is the microwave frequency, c is the speed of light, μ_r and ε_r are 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]:

$$Z_c(TE) = \frac{E_t}{H_t \cos \theta_t} = \frac{\sqrt{\mu/\epsilon}}{\cos \theta_t} = \frac{\sqrt{\mu_r \mu_0 / \epsilon_r \epsilon_0}}{\cos \theta_t}, \quad (2)$$

$$Z_c(TM) = \frac{E_t \cos \theta_t}{H_t} = \sqrt{\mu/\epsilon} \cos \theta_t = \sqrt{\mu_r \mu_0 / \epsilon_r \epsilon_0} \cos \theta_t, \quad (3)$$

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

where μ and ϵ are the permeability and permittivity of the absorber, respectively, and μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ H/m) and ϵ_0 is the permittivity of free space (8.854×10^{-12} F/m). The relationship between incident angle and refraction angle is given by Snell's law:

$$\theta_t = \arccos \sqrt{1 - \frac{\sin^2 \theta_i}{\epsilon_r \mu_r}}. \quad (5)$$

According to transmission line theory, reflection **losses** for TE and TM polarizations **are** given by

$$RL(TE) = 20 \log \left| \frac{Z_{in} - Z_0 / \cos \theta_i}{Z_{in} + Z_0 / \cos \theta_i} \right|, \quad (6)$$

$$RL(TM) = 20 \log \left| \frac{Z_{in} - Z_0 \cos \theta_i}{Z_{in} + Z_0 \cos \theta_i} \right|. \quad (7)$$

The reflection loss of the absorber for TE and TM polarizations can thus be derived and given by

$$RL(TE) = 20 \log \left| \frac{\frac{\sqrt{\mu_r/\epsilon_r}}{\sqrt{1 - \frac{\sin^2 \theta_i}{\epsilon_r \mu_r}}} \tanh \left[j \frac{2\pi f}{c} \sqrt{\epsilon_r \mu_r} \sqrt{1 - \frac{\sin^2 \theta_i}{\epsilon_r \mu_r}} d \right] - \frac{1}{\cos \theta_i}}{\frac{\sqrt{\mu_r/\epsilon_r}}{\sqrt{1 - \frac{\sin^2 \theta_i}{\epsilon_r \mu_r}}} \tanh \left[j \frac{2\pi f}{c} \sqrt{\epsilon_r \mu_r} \sqrt{1 - \frac{\sin^2 \theta_i}{\epsilon_r \mu_r}} d \right] + \frac{1}{\cos \theta_i}} \right|, \quad (8)$$

$$RL(TM) = 20 \log \left| \frac{\sqrt{\mu_r/\epsilon_r} \sqrt{1 - \frac{\sin^2 \theta_i}{\epsilon_r \mu_r}} \tanh \left[j \frac{2\pi f}{c} \sqrt{\epsilon_r \mu_r} \sqrt{1 - \frac{\sin^2 \theta_i}{\epsilon_r \mu_r}} d \right] - \cos \theta_i}{\sqrt{\mu_r/\epsilon_r} \sqrt{1 - \frac{\sin^2 \theta_i}{\epsilon_r \mu_r}} \tanh \left[j \frac{2\pi f}{c} \sqrt{\epsilon_r \mu_r} \sqrt{1 - \frac{\sin^2 \theta_i}{\epsilon_r \mu_r}} d \right] + \cos \theta_i} \right|. \quad (9)$$

As suggested by Eqs. (8) and (9), reflection losses for TE and TM polarizations at different angles of incidence depend on the dielectric properties of the absorbers at a given frequency and temperature. Based on the variation of reflection loss with incident angle, the microwave absorption characteristics of SiC and Al₂O₃ under oblique incident microwave irradiation can be determined. The dielectric properties of SiC and Al₂O₃ at the most commonly used microwave frequency (2.45 GHz) are summarized in Table 1 [19, 20]. The values for μ_r of SiC and Al₂O₃ are assumed to be 1 in the RL calculations ($\mu_r' = 1$ and $\mu_r'' = 0$).

3. Results and Discussion

As aforementioned, the reflection loss depends on the ceramic absorber thickness. To evaluate the variation of microwave reflection loss with incident angle, it is necessary to select an appropriate thickness, or the impedance matching thickness, at which high microwave

absorption in the ceramics can be achieved [18]. In the thickness ranging up to 0.10 m, the matching thicknesses for microwave heating of a SiC layer and an Al₂O₃ layer were found to be 0.0054 and 0.923 m, respectively [15]. At these thicknesses, the reflection losses of SiC and Al₂O₃ over the incident angle range from 0 to 90° at room temperature can be determined. The *RL* patterns in Fig. 2 show that SiC and Al₂O₃ have distinct variations in reflection loss for TE and TM polarizations. For SiC, the *RL* values for TE polarization are larger than those for TM polarization in the entire incident angle range, suggesting weaker absorption in SiC under microwave irradiation with TE polarization. Further, it is shown that high absorption in SiC can only be obtained at small angles for TE polarization. The value of *RL* monotonically increases with increasing angle from 0 to 90°, demonstrating that microwave absorption is reduced at high incident angles. For TM polarization, strong absorption in SiC is found at high incident angles (60° < θ_i < 80°) and the minimum reflection loss ($RL_{min} = -31.8274$ dB) occurs at 74.4709° (Table 2). The difference between TE and TM polarizations can be attributed to the effect of Brewster's angle at which microwaves are perfectly transmitted through the material without reflection. Brewster's angles (θ_B) for TE and TM polarizations are determined by [21]

$$\theta_B(TE) = \arcsin\left(\sqrt{\frac{1 - \mu_0 \varepsilon / \mu \varepsilon_0}{1 - (\mu_0 / \mu)^2}}\right) = \arcsin\left(\sqrt{\frac{1 - \varepsilon_r / \mu_r}{1 - (1 / \mu_r)^2}}\right), \quad (10)$$

$$\theta_B(TM) = \arcsin\left(\sqrt{\frac{1 - \mu \varepsilon_0 / \mu_0 \varepsilon}{1 - (\varepsilon_0 / \varepsilon)^2}}\right) = \arcsin\left(\sqrt{\frac{1 - \mu_r / \varepsilon_r}{1 - (1 / \varepsilon_r)^2}}\right). \quad (11)$$

As seen from Eqs. (10) and (11), Brewster's angle depends on the complex relative permittivity for nonmagnetic ceramics. Specifically, the angle is principally determined by ε_r' , even if the material has a quite high ε_r'' . The calculation shows that Brewster's angle does not exist for TE polarization, giving rising to the monotonic increase of *RL* with increasing θ_i . For TM

polarization, however, Brewster's angle is found to be approximately 79.036° , approaching the angle at which RL_{min} takes place.

Compared with SiC, microwave absorption in Al_2O_3 shows a negligible difference between TE and TM polarizations. Relatively high microwave absorption can only be obtained at small incident angles ($< 20^\circ$). This **phenomenon** is clearly shown in Fig. 2 and by Table 2 that the RL_{min} values for TE and TM polarizations are, respectively, -0.3833 and -0.3792 dB. Additionally, it is interesting to observe that Al_2O_3 shows RL_{min} at 12.3884° for TE polarization, indicating this particular angle is associated with Al_2O_3 microwave dielectric loss. Because Al_2O_3 is a low-loss absorber with a fairly low dielectric loss factor (Table 1), microwaves penetrate the material and are reflected back by the metal (cavity wall) without much dissipation. This leads to multiple absorption peaks caused by “standing waves” formed within the material, making the absorption behavior increasingly complex [22,23].

Many ceramics exhibit a strong temperature dependence of microwave absorption, suggesting that ceramics subjected to oblique incident microwave irradiation should be examined at high temperatures. Figs. 3 and 4 show the reflection loss of Al_2O_3 as a function of incident angle at various temperatures for TE and TM polarizations, respectively. As the permittivity of Al_2O_3 increases with temperature, the RL_{min} values and corresponding incident angles show frequent fluctuations in the entire temperature range for TE polarization (Table 3). Here, it can be seen that microwave absorption will increase substantially at a specific angle. For example, the RL_{min} value decreases from -0.3833 to -9.9401 dB as temperature increases from 22 to 491 $^\circ C$. However, the value of RL_{min} then increases with increasing temperature up to 1050 $^\circ C$ and decreases again at 1379 $^\circ C$. These fluctuations indicate that it is difficult to predict absorption in low-loss materials for TE polarization, primarily due to the absence of an alternating electric

field in the direction of microwave propagation. Conversely, for TM polarization, reflection loss of Al_2O_3 varies monotonically with θ_i as the temperature is increased, shown by a decreasing RL_{min} value when the corresponding incident angle increases. The results agree well with the fact that microwave dielectric loss of Al_2O_3 dominates power absorption in the material and the microwave penetration depth decreases with increasing temperature. It is clear that TM-polarized microwaves aid reduction in reflection losses of both high- and low-loss ceramics. Microwave absorption in ceramics throughout the heating process can be improved by modifying the incident angle and microwave polarization type.

4. Conclusions

The characteristics of microwave absorption in single-layer ceramics under oblique incident microwave irradiation have been studied by exploring the impact of incident angle on microwave reflection losses of a high-loss SiC layer and of a low-loss Al_2O_3 layer for both TE and TM polarizations. The reflection losses of the ceramic layers with matching thicknesses of 0.0054 and 0.923 m, respectively, were determined in the incident angle range from 0 to 90° using the derived RL equations. The results show that 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. As the RL increases with incident angle, high absorption in SiC can only be obtained at small angles for TE polarization. On the other hand, stronger absorption in SiC is expected at large incident angles for TM polarization. This observation is explained by the effect of Brewster's angle. For Al_2O_3 at room temperature, the RL_{min} values for TE and TM polarizations are -0.3883 and -0.3792 dB, respectively, suggesting negligible differences between TE and TM polarizations due to low dielectric loss. When the temperature increases

from room temperature to 1379 °C, the RL_{min} values of Al_2O_3 for TE polarization show frequent fluctuations in the entire temperature range, demonstrating the difficulty in predicting absorption in low-loss materials for TE polarization. For TM polarization, reflection loss of Al_2O_3 varies monotonically with θ_i as the temperature is increased, shown by a decreasing RL_{min} value when the corresponding incident angle increases. The results agree well with the fact that dielectric loss of Al_2O_3 is the main source of power absorption and that microwave penetration depth decreases with increasing temperature. It has been demonstrated that TM-polarized microwaves enable reduction in reflection losses of both high- and low-loss ceramics. Modifying incident angle and microwave polarization type can improve power absorption in ceramics throughout the heating process.

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Table captions:

Table 1 Microwave dielectric properties of SiC and Al₂O₃ at 2.45 GHz [19,20].

Table 2 Minimum reflection losses and corresponding incident angles of SiC and Al₂O₃ at 22 °C for TE and TM polarizations.

Table 3 Minimum reflection losses and corresponding incident angles of Al₂O₃ at different temperatures for TE and TM polarizations.

Figure captions:

Fig. 1. Schematic of TE and TM polarizations in which incident, transmitted, 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.

Fig. 2. Variation of reflection losses of SiC and Al_2O_3 with incident angle at 22 °C for TE and TM polarizations: (a) SiC, TE, (b) Al_2O_3 , TE, (c) SiC, TM, and (d) Al_2O_3 , TM.

Fig. 3. Variation of reflection loss of Al_2O_3 with incident angle at high temperatures for TE polarization: (a) 491 °C, (b) 871 °C, (c) 1050 °C, and (d) 1379 °C.

Fig. 4. Variation of reflection loss of Al_2O_3 with incident angle at high temperatures for TM polarization: (a) 491 °C, (b) 871 °C, (c) 1050 °C, and (d) 1379 °C.

Table 1

Table 1

Microwave dielectric properties of SiC and Al₂O₃ at 2.45 GHz [19,20].

Parameter	SiC	Al ₂ O ₃				
		22 °C	491 °C	871 °C	1050 °C	1379 °C
ϵ_r'	26.66	8.9	9.82	10.4	10.81	11.77
ϵ_r''	27.99	0.004	0.025	0.093	0.158	0.476

Table 2

Minimum reflection losses and corresponding incident angles of SiC and Al₂O₃ at 22 °C for TE and TM polarizations.

Polarization	SiC		Al ₂ O ₃	
	<i>RL_{min}</i> (dB)	<i>θ</i> (°)	<i>RL_{min}</i> (dB)	<i>θ</i> (°)
TE	-10.1692	0	-0.3833	12.3884
TM	-31.8274	74.4709	-0.3792	0

Table 3

Minimum reflection losses and corresponding incident angles of Al₂O₃ at different temperatures

for TE and TM polarizations.

Polarization	22 °C		491 °C		871 °C		1050 °C		1379 °C	
	<i>RL_{min}</i> (dB)	<i>θ</i> (°)	<i>RL_{min}</i> (dB)	<i>θ</i> (°)	<i>RL_{min}</i> (dB)	<i>θ</i> (°)	<i>RL_{min}</i> (dB)	<i>θ</i> (°)	<i>RL_{min}</i> (dB)	<i>θ</i> (°)
TE	-0.3833	12.3884	-9.9401	77.9287	-1.4620	64.5441	-1.4106	0	-4.7028	0
TM	-0.3792	0	-1.3578	52.7588	-3.2901	65.3100	-4.8981	72.8487	-34.8947	84.1648

Figure 1

Figure 2

a

b

c

d

Figure 3

Figure 4