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Design of double-layer ceramic absorbers for microwave heating

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Abstract

We propose a guide for designing double-layer ceramic absorbers in microwave heating by optimizing the thickness based on the analysis of reflection loss (RL) of a double-layer absorber consisting of a high-loss SiC layer and a low-loss Al_2O_3 layer. The calculated reflection losses for individual layers of SiC and Al_2O_3 show that the former with a thickness of 0.0054 m has the maximum microwave absorption while the latter in the thickness range up to 0.1 m is identified as a poor microwave absorbing material with RL larger than −0.4 dB. By using a 0.0054-m-thick SiC layer as the susceptor, the absorption in the Al_2O_3 layer and of the entire double-layer absorber increases significantly. The results demonstrate that high microwave absorption throughout the heating process can only be achieved in a sample with a small thickness in which a slight absorption peak shift during heating (less than one eighth-wavelength in the medium) occurs.

Keywords: A. Microwave processing; D. Al_2O_3; D. SiC; Double-layer absorbers

1. Introduction

Microwave energy has been widely applied in the processing of various ceramic materials including those having relatively low microwave absorption capabilities (low-loss absorbers, i.e., Al_2O_3) [1–6]. To enhance the heating process of poor microwave absorbing materials, a susceptor with good microwave absorption properties and high thermal conductivity (e.g., high-loss SiC) is commonly used [7]. Generally, the susceptor combined with the sample constitutes a double-layer absorber, which has raised extensive interest from many researchers [8,9].

To achieve maximum microwave absorption throughout the heating process, a design for obtaining optimal dimensions (e.g., optimum thickness of each layer) of the double-layer absorber becomes extremely important and has to be implemented due to a strong sample dimension dependence of microwave power absorption in materials. Although the importance of absorber design in microwave heating has been demonstrated by experimental work, a general rule for the design of the absorber from a theoretical viewpoint is not available. Recent work indicates that the analysis of reflection loss (RL) of materials may be helpful in the design of an individual absorber throughout microwave heating by simultaneously considering the effects of various factors (permittivity, permeability, absorber dimension, microwave frequency, etc.) that influence the power absorbed in the material [10].

For design of double-layer ceramic absorbers, there is no detailed study considering the temperature and frequency dependences of microwave absorption properties and the interaction between different layers. A valid design rule for double-layer absorbers is still highly demanded. In order to address this issue, the current work is devoted to achieve the maximum microwave absorption in a double-layer ceramic absorber by studying the reflection losses of the absorber and its individual layers. The RL characteristics of the microwave double-layer absorber consisting of a SiC susceptor layer and an Al_2O_3 layer in a broad temperature range up to ~1400 °C are determined using formulas derived from the transmission line theory. The results

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provide a general guide for microwave absorber design, which could provide insight on achieving the maximum absorption during microwave processing of ceramics.

2. Theory of reflection loss

Fig. 1 shows a double-layer absorber consisting of an Al_2O_3 layer and a SiC susceptor layer backed by a metallic cavity wall under microwave irradiation. According to the transmission line theory [11], the following equations can be derived and used to determine the reflection loss (RL) of the double-layer absorber:

$$RL = 20\ \log\left|\frac{Z_{in}-\eta_0}{Z_{in}+\eta_0}\right|, \tag{1}$$

$$Z_{in} = \eta_2 \frac{Z_1+\eta_2 \tanh\,[j(2\pi f)/c)\sqrt{\mu_{r,2}\varepsilon_{r,2}}d_2]}{\eta_2+Z_1 \tanh\,[j(2\pi f)/c)\sqrt{\mu_{r,2}\varepsilon_{r,2}}d_2]}, \tag{2}$$

$$Z_1 = \eta_1 \tanh\left(j\frac{2\pi f}{c}\sqrt{\mu_{r,1}\varepsilon_{r,1}}d_1\right), \tag{3}$$

$$\eta = \sqrt{\frac{\mu_r\mu_0}{\varepsilon_r\varepsilon_0}}, \tag{4}$$

where Z and η denote the input impedance and characteristic impedance, respectively, of a given medium indicated by the corresponding subscript; the subscripts, *in*, 0, 1, and 2 represent the double-layer absorber, free space, SiC, and Al_2O_3, respectively; 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 ($\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$), respectively, of the given medium which include real (μ_r', ε_r') and imaginary parts (μ_r'', ε_r''), d is the thickness of the medium, μ_0 and ε_0 are the permeability and permittivity of free space, respectively.

As indicated by Eqs. (1)–(4), reflection loss of the double-layer absorber depends on the microwave dielectric properties of the SiC and Al_2O_3 layers at a given frequency and temperature. These properties of the materials in the temperature range from 22 to 1379 °C at 2.45 GHz are summarized in Table 1 [12,13]. The temperature and thickness dependences of reflection loss of the absorber can be determined based on the reported parameters. The values of μ_r of SiC and Al_2O_3 are assumed to be 1 in the RL calculations ($\mu_r' = 1$ and $\mu_r'' = 0$).

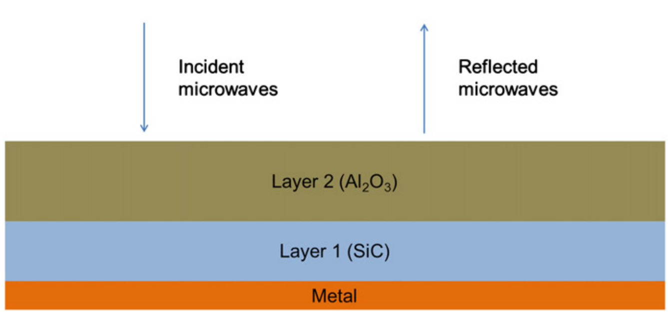

Fig. 1. Schematic of a double-layer absorber under microwave irradiation.

Table 1
Microwave absorption properties of Al_2O_3 and SiC at 2.45 GHz.

Parameters	Al_2O_3					SiC
	22 °C	491 °C	871 °C	1050 °C	1379 °C	
ε_r' [a]	8.9	9.82	10.4	10.81	11.77	26.66
ε_r'' [a]	0.004	0.025	0.093	0.158	0.476	27.99
D_p (m)	14.535	2.443	0.676	0.406	0.140	0.004
λ_m (m)	0.041	0.039	0.038	0.037	0.036	0.021

[a]Data taken from Refs. [12,13].

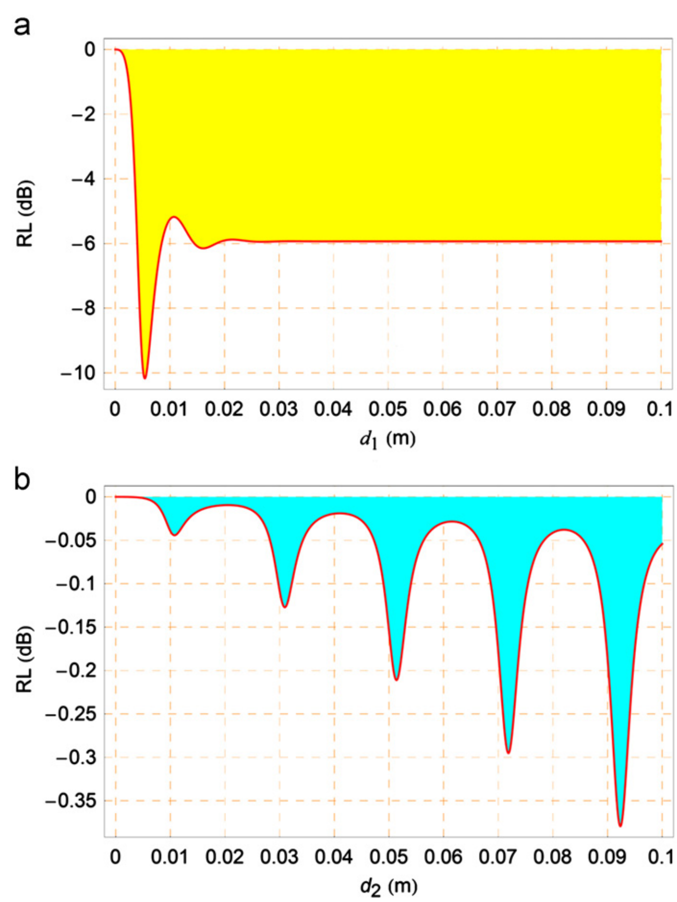

Fig. 2. RL patterns of individual layers of (a) SiC and (b) Al_2O_3 at room temperature.

3. Results and discussion

To study the overall absorption performance of the double-layer absorber, it is helpful to perform a preliminary study on the reflection loss characteristics of individual layers of SiC and Al_2O_3. The RL pattern of SiC in Fig. 2(a) shows a sharp microwave absorption peak, indicated by a RL trough (RL = −10.1693 dB), when SiC has a thickness of 0.0054 m. The formation of the peak can be attributed to the short microwave penetration depth (D_p) of SiC (Table 1). The value of D_p is determined by [14,15]

$$D_p = \frac{\lambda_0}{2\sqrt{2}\pi}\{\varepsilon''_r\mu''_r - \varepsilon'_r\mu'_r + [(\varepsilon'_r\mu'_r)^2 + (\varepsilon''_r\mu''_r)^2 + (\varepsilon'_r\mu''_r)^2 + (\mu'_r\varepsilon''_r)^2]^{1/2}\}^{-1/2}, \quad (5)$$

where λ_0 is the microwave length in free space. This finding suggests that the thickness optimization for each absorber layer is necessary for efficient microwave heating; SiC with a thickness of 0.0054 m should be used as the susceptor layer to achieve the highest microwave absorption for rapid microwave heating of the double-layer absorber. Further, a susceptor with a small thickness is beneficial for heat conduction from SiC to Al_2O_3 during the initial heating. This is very important for heating the double-layer absorber because Al_2O_3 is a poor microwave absorbing material, as demonstrated by its large reflection loss (RL > −0.4 dB as d_2 varies from 0 to 0.1 m) in Fig. 2(b).

Now having the optimal thickness of SiC (d_1=0.0054 m), the variation of RL of the double-layer absorber with the thickness of Al_2O_3 in the temperature range can be determined. The results are presented in Fig. 3.

Comparison between Figs. 2 and 3 clearly shows that the use of a susceptor effectively increases the microwave absorption in the Al_2O_3 layer and of the whole absorber. Inspection of Fig. 3 suggests that there are 5 absorption peaks in the RL patterns. The peak positions (d_{peak}) at various temperatures are listed in Table 2. Peak 1 at 22 °C indicates that the Al_2O_3 layer with a thickness of 0.0068 m exhibits the maximum microwave absorption (RL = −23.4032 dB). However, as temperature increases, a shift of peak position (Δd_{peak}) is observed. For instance, the peak shifts from 0.0068 to 0.0050 m as the temperature increases from 22 to 1379 °C. This suggests that a smaller thickness of Al_2O_3 is required to achieve the maximum absorption at an elevated temperature. A temperature dependence of sample thickness corresponding to the maximum absorption is also observed in other peaks. This phenomenon can be explained by the increased microwave phase constant

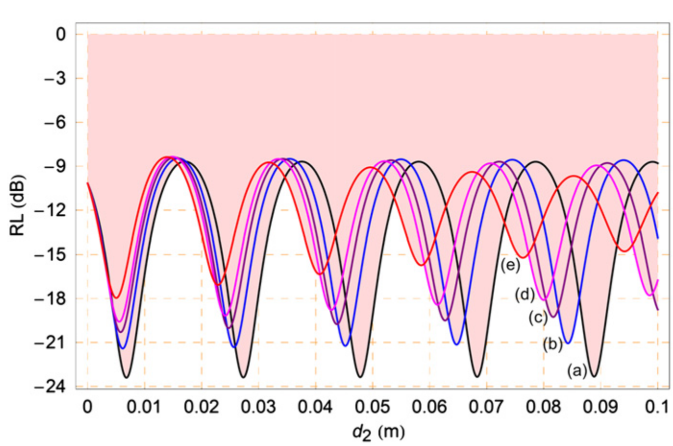

Fig. 3. Temperature dependence of RL of the double-layer absorber as the thickness of the Al_2O_3 layer varies from 0 to 0.1 m: (a) 22 °C, (b) 491 °C, (c) 871 °C, (d) 1050 °C, and (e) 1379 °C.

and, therefore, a shorter microwave wavelength in the medium (λ_m) as the temperature increases (Table 1). The value of λ_m is determined by [16]

$$\lambda_m = \sqrt{2}\lambda_0\{\varepsilon'_r\mu'_r - \varepsilon''_r\mu''_r + [(\varepsilon'_r\mu'_r)^2 + (\varepsilon''_r\mu''_r)^2 + (\varepsilon'_r\mu''_r)^2 + (\mu'_r\varepsilon''_r)^2]^{1/2}\}^{-1/2}. \quad (6)$$

It is also noted that, for all absorption peaks (Peaks 1–5) in the RL patterns, their intensity decreases (RL increases) with increasing temperature. For example, RL of Peak 1 increases from −22.4032 to −17.9586 dB as temperature increases from 22 to 1379 °C. This can be attributed to the fact that microwave penetration depth of the material decreases with increasing temperature, as illustrated in Table 1.

It seems difficult to optimize absorber thickness for achieving the highest power absorption throughout the microwave heating process because of the temperature dependence of the shift of microwave absorption peaks and the variation of peak intensity. However, one may anticipate that a suitable absorber thickness should be limited in the range indicated by the positions of the absorption peaks in the temperature range (i.e., $d_{peak,\ 22\ °C} \le d_2 \le d_{peak,\ 1379\ °C}$). This suggests that five thicknesses (d_2=0.006, 0.025, 0.045, 0.060, and 0.080 m) for the Al_2O_3 layer corresponding to the five peaks in the RL patterns may be chosen for achieving high power absorption in the examined dimension range during the entire microwave heating process.

Fig. 4 shows the temperature dependence of RL of the double-layer absorber as the thickness of the Al_2O_3 layer varies from 0.006 to 0.080 m. It is seen from Fig. 4 that the absorber has the maximum absorption in the temperature range (−22.67 dB ≤ RL ≤ −17.26 dB) when the Al_2O_3 layer has a thickness of 0.006 m, which corresponds to Peak 1 in Fig. 3. This RL range indicates that less than 2% power is reflected from the surface of the absorber throughout the heating process. The high power absorption is essentially attributed to a small peak shift in the temperature range ($\Delta d_{peak} = d_{peak,\ 22\ °C} - d_{peak,\ 1379\ °C} \le \lambda_m/8$). For the layer with a larger thickness, however, microwave absorption tends to decrease. This is particularly true for the Al_2O_3 layer having a thickness greater than 0.045 m due to a significant variation of RL with temperature. The RL ranges for the entire absorber are found to be −17.29 dB ≤ RL ≤ −9.13 dB and −18.09 dB ≤ RL ≤ −8.93 dB as the thickness of the Al_2O_3 layer is increased to 0.060 m (Peak 4) and 0.080 m (Peak 5), respectively. The considerable decrease in microwave absorption is closely associated with the large peak shift in the RL patterns as the temperature varies. As shown in Table 2, the amounts of peak shift between 22 and 1379 °C for Peak 4 and Peak 5 are larger than one quarter-wavelength in the medium ($\Delta d_{peak} > \lambda_m/4$). This observation indicates that it is impossible to attain high microwave absorption throughout the entire heating process by optimizing thickness for an absorber having a large absorption peak shift in the

Table 2
Absorption peaks in the RL patterns of the double-layer absorber at various temperatures.

Peak nos.	22 °C		491 °C		871 °C		1050 °C		1379 °C	
	d_{peak} (m)	RL (dB)	d_{peak} (m)	RL (dB)	d_{peak} (m)	RL (dB)	d_{peak} (m)	RL (dB)	d_{peak} (m)	RL(dB)
1	0.0068	−23.4032	0.0061	−21.4088	0.0058	−20.2929	0.0055	−19.5819	0.0050	−17.9586
2	0.0273	−23.3840	0.0257	−21.3188	0.0247	−20.0150	0.0241	−19.1666	0.0228	−17.0707
3	0.0478	−23.3649	0.0452	−21.2300	0.0437	−19.7501	0.0427	−18.7818	0.0407	−16.3379
4	0.0683	−23.3459	0.0647	−21.1425	0.0627	−19.4975	0.0614	−18.4245	0.0585	−15.7271
5	0.0888	−23.3269	0.0842	−21.0562	0.0817	−19.2564	0.0800	−18.0922	0.0763	−15.2137

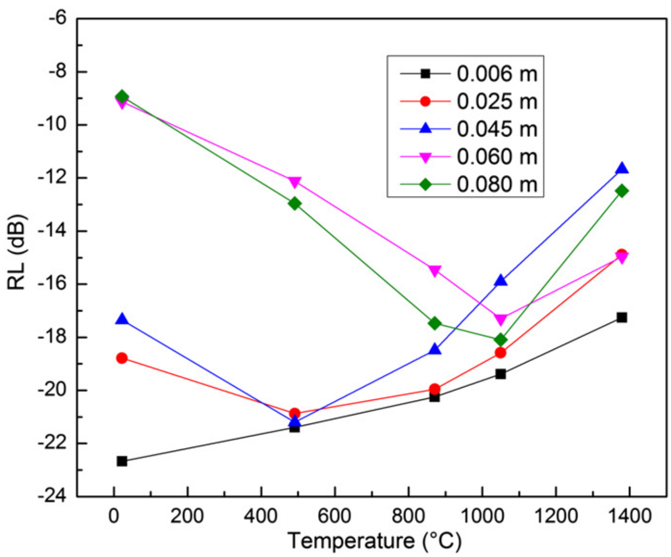

Fig. 4. Temperature dependence of RL of the double-layer absorber as the thickness of the Al_2O_3 layer varies from 0.006 to 0.080 m.

temperature range (i.e., $\Delta d_{peak} > \lambda_m/4$). Conversely, high microwave absorption can only be achieved in a sample with a thickness in which a slight absorption peak shift (i.e., $\Delta d_{peak} < \lambda_m/8$) occurs.

4. Conclusions

The design of a double-layer ceramic absorber consisting of a SiC susceptor layer and an Al_2O_3 layer under microwave irradiation has been performed by optimizing its thickness based on the analysis of reflection loss. A preliminary study on the reflection losses of individual layers of SiC and Al_2O_3 shows that the former with a thickness of 0.0054 m has strong microwave absorption, while the latter in the thickness range up to 0.1 m is identified as a poor microwave absorbing material with RL larger than −0.40 dB. By using a 0.0054-m-thick SiC layer as the susceptor, microwave absorption in the Al_2O_3 layer and of the double-layer absorber increases substantially. The variation of RL of the absorber with the thickness of the Al_2O_3 layer suggests that a smaller thickness of Al_2O_3 is required to achieve the highest absorption in the absorber at a high temperature. The intensity of microwave absorption peaks in the RL patterns of the double-layer absorber decreases with increasing temperature. It is impossible to obtain high microwave absorption throughout the entire heating process by optimizing thickness for an absorber having a large absorption peak shift during heating (i.e., $\Delta d_{peak} > \lambda_m/4$). In contrast, high microwave absorption throughout the heating process can only be achieved in the sample with a small thickness in which a slight absorption peak shift (i.e., $\Delta d_{peak} < \lambda_m/8$) occurs.

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