J Mater Sci (2007) 42:3251–3254
DOI 10.1007/s10853-006-1413-9

A method for the evaluation of electromagnetic wave absorption potential using surface temperature change under microwave irradiation

K. Matsumura · Y. Kagawa

Received: 13 November 2005 / Accepted: 17 February 2006 / Published online: 15 January 2007

Abstract Absorption behavior of electromagnetic wave by spherical H_2O-filled SiO_2 shell microcapsule-dispersed paraffin matrix composites is evaluated using a microwave heating and thermographic system. The composites under microwave irradiation show temperature change at the specimen surface. The temperature rises as an increase of a volume fraction of H_2O and the absorption of electromagnetic wave is strongly correlated with the temperature rise.

Introduction

Electromagnetic wave absorbing materials have recently received special attention because extensions of wireless technology have demonstrated an interest for them. Electromagnetic wave absorbing materials usually use two kinds of mechanisms: (i) energy conversion from incident wave energy into Joule energy by dielectric loss or magnetic loss mechanisms, and (ii) dissipation of electromagnetic wave using interference by geometric structures such as a quarter-wavelength layer etc [1]. Both of the mechanisms are applied to the existing electromagnetic absorbing materials.

The evaluation of electromagnetic wave absorption potential is important and various techniques have been developed [2–6]. Usually, the absorbing potential of materials have been evaluated through the measurement of reflectance and transmittance of electromagnetic waves using the appropriate electronic systems [7, 8]. At the same time, indirect evaluation of the potential has been done through measurements of physical properties, such as conductivity and dielectric constant etc [9, 10]. In these methods, however, the measured properties are difficult to correlate with the actual absorbing behavior of individual constituent materials in regards to the entire electromagnetic absorbing materials.

In the present paper, a new method to evaluate a temperature change by the electromagnetic wave absorption has been proposed by using surface temperature measurement equipment on well-characterized model materials.

Experimental procedure

Figure 1 shows a schematic drawing of the microwave-heating set-up, which consists of a microwave heating source (Kanto Electronics Application & Development Inc., Tokyo, Japan) and an infrared thermography camera (TVS-8500: Nippon Avionics Co., Tokyo). The camera detects an infrared light in a wavelength range from 3.5×10^{-6} to 4.1×10^{-6} and from 4.5×10^{-6} to 5.1×10^{-6} m with a nominal temperature resolution of 0.025 K. Appearance of the experimental set-up is shown in Fig. 2. The microwave-heating source emits a 2.45 GHz (a wavelength λ of ≈ 0.12 m) electromagnetic wave from a pyramidal horn antenna. Nominal output power of the system was controlled using a H_2O absorber, which is placed between the amplifier and antenna. The used nominal output power of the system

K. Matsumura · Y. Kagawa (✉)
Research Center for Advanced Science and Technology,
The University of Tokyo, 4-6-1, Komaba, Meguro-ku,
Tokyo 153-8505, Japan
e-mail: kagawa@iis.u-tokyo.ac.jp

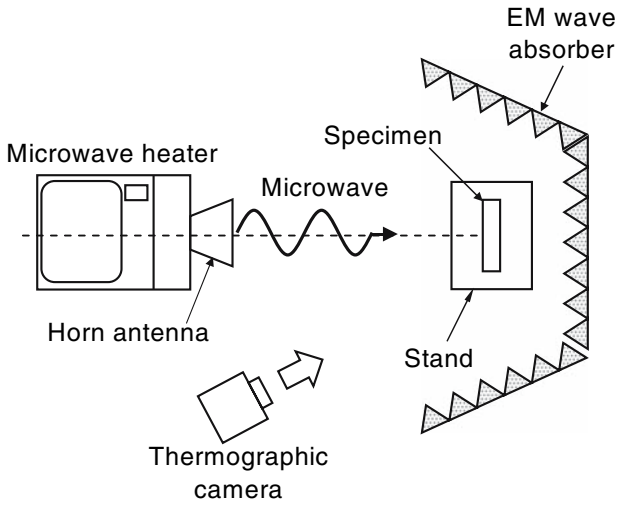

Fig. 1 A schematic drawing of the microwave heating system

was ~100 W. Specimen holder with a low electromagnetic wave absorbing material was located about 0.3 m from the exit plane of the horn antenna to allow normal incidence of an electromagnetic wave to the specimen surface. The electromagnetic irradiation system was covered with a commercially available pyramid type polymer-base electromagnetic wave absorbing material for a purpose of safety operation.

The spherical H_2O-filled SiO_2 shell microcapsule-dispersed paraffin matrix composites were used as the heating target model material. This composite was chosen because it has been known that H_2O has a resonance frequency of $f = 2.45$ GHz by a molecular vibration of H–O bond [11] and this property is effective in detecting the electromagnetic absorption potential. The composite material was prepared by mixing H_2O-filled SiO_2 microcapsule (Washin Kagaku Co., Shizuoka, Japan) with a paraffin matrix ($C_{24}H_{50}$), which was heated at a temperature of 333 K. A schematic drawing of the microstructure of the composite is shown in Fig. 3. The microcapsules used had a spherical shape with its shell thickness of 2~3 nm. The outer diameter of the spherical capsule, d_p, distributed from 3 μm to 12 μm with its most available size of ~5 μm [12]. A plate-shaped composite was made by casting the mixture of the H_2O contained microcapsule and paraffin into a teflon-coated stainless tray. The specimen thickness, d_s, was from 3 to 11 mm.

Volume fraction of H_2O, f_p, in the entire composite was varied from $f_p = 0.08$ to 0.23 and 0.38. Here, the value of f_p is defined as a net total volume fraction of H_2O in the composite. The volume of spherical SiO_2 shell was incorporated in the volume of paraffin matrix. Actually, because of the thin SiO_2 shell structure, total volume fraction of the shell was less than 0.02 f_p and was considerably smaller than f_p. Under this assumption, the volume fraction of H_2O is given by,

$$f_p = \frac{(w_{H_2O} - w_{SiO_2})/\rho_{H_2O}}{(w_{H_2O+SiO_2} - w_{SiO_2})/\rho_{H_2O} + w_{SiO_2}/\rho_{SiO_2} + w_{C_{24}H_{50}}/\rho_{C_{24}H_{50}}} \quad (1)$$

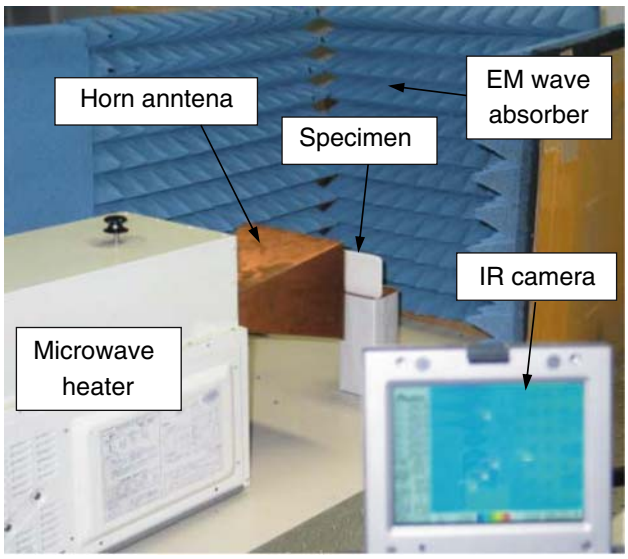

Fig. 2 Appearance of the experimental set-up

where w_{SiO_2}, $w_{H_2O+SiO_2}$ and $w_{C_{24}H_{50}}$, respectively, are the net weights of dry SiO_2 shell, the H_2O-filled microcap-

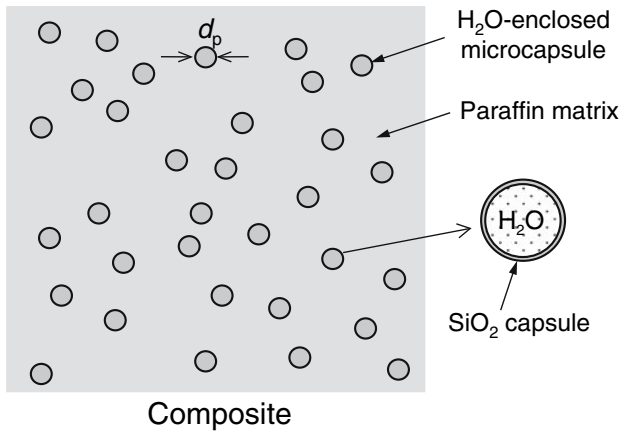

Fig. 3 Schematic drawing of the microstructure of the composite

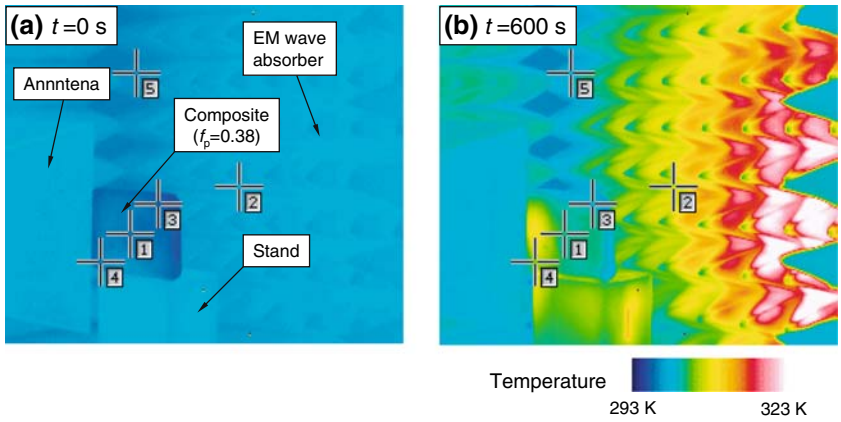

Fig. 4 Typical temperature distributions of the composite (f_p = 0.38) before the irradiation (t = 0 s) (**a**) and after the heating (t = 600 s) (**b**)

sules, and the $C_{24}H_{50}$, and1 ρ_{H_2O} (=0.997 g cm^{-3} [13]), ρ_{SiO_2} (=2.65 g cm^{-3} [14]), and $\rho_{C_{24}H_{50}}$ (=0.88 g cm^{-3}) are the density of H_2O, SiO_2, and $C_{24}H_{50}$ at room temperature, respectively. Here, the density of $C_{24}H_{50}$ is obtained from an experiment based on Archimedes' principle.

Results and discussion

Figure 4 shows typical temperature distributions of the composite (f_p=0.38) before irradiation (t = 0 s) (a) and after irradiation from the electromagnetic wave (t = 600 s) (b). Before irradiation, a constant surface temperature over the entire composite is shows (~297 K). However, after irradiation of electromagnetic wave, a rise in temperature behavior is clearly observed although the distribution of temperature at the measured surface is non-uniform. The non-uniform temperature distribution is remarkable especially at the edge of the specimen. With an irradiation time of t = 6 ks, the surface temperature of composite at a central part reached to ~303 K. This temperature is about 6 K higher than that measured before the irradiation. This temperature rise behavior clearly suggests absorption of electromagnetic wave by the composite. Hereafter, temperature at the center surface of the specimen is used for discussion.

Electromagnetic wave absorption potential of the composite could be compared by using a normalized temperature, $\langle T \rangle$, because the major electromagnetic absorption of the composite appears as the electromagnetic wave changes into Joule heat energy. It should be noted, however, that the absorption by the paraffin matrix and spherical shell is much smaller than that of H_2O because of the strong electromagnetic resonance of H_2O at a frequency of 2.45 GHz. Here, the normalized temperature is defined as

$$\langle T \rangle = \frac{T_c}{T_0} \tag{2}$$

where T_c is the average temperature of three different points at the specimen surface and T_0 is that of the pure paraffin specimen. Fig. 5 shows the normalized temperature, $\langle T \rangle$, *vs.* heating time, t, for the composite with different H_2O contents. Just after the irradiation, the normalized temperature shows an unstable behavior and this behavior continues for t ~ 200 s. The temperature becomes nearly constant after t~400 s. The temperature of the composite with f_p = 0.23, and 0.38 at first decreases and then slightly increases with the increase in irradiation time, probably due to thermal conductivity effect of the composite specimen. Rapid absorption of electromagnetic wave causes a local increase in the temperature of the SiO_2 spherical shell containing H_2O and the temperature decreases by heat conduction toward the inside of the composite and/or thermal radiation from the surface. This effect becomes small in the low H_2O content composite (f_p = 0.08) and only a slight increase appears in the composite with f_p = 0.08. After t > 400 s, the normalized temperature of the composites exhibits a temperature higher than that of the pure matrix, and the temperature of the composite with the same irradiation time becomes larger with increasing the volume fraction of H_2O, f_p. This result indicates that a steady state temperature at the surface of an irradiated composite appears after t ~ 400 s. That is, electromagnetic wave absorbing behavior of the composite could be evaluated through the rise in surface temperature.

Figure 6 shows the relationship between normalized temperature, $\langle \tilde{T} \rangle$ and particle volume fraction, f_p. Here, the normalized temperature is obtained by averaging $\langle T \rangle$ after steady state ($t \geq$ 400 sec), i.e.,

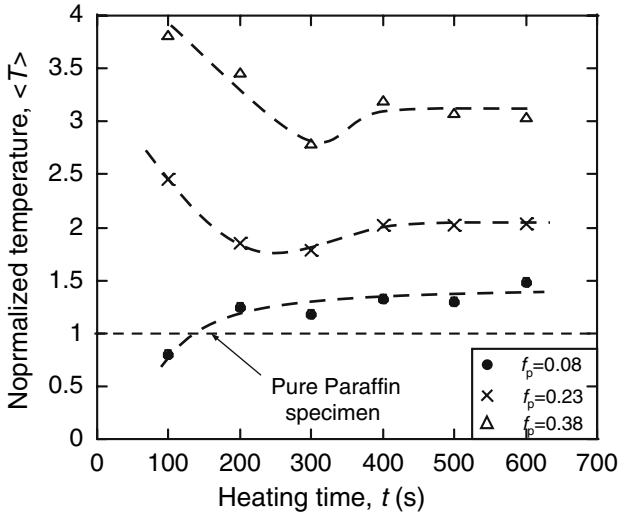

Fig. 5 Normalized temperature, $\langle T \rangle$, *vs.* heating time, t, for the composite with different H_2O contents

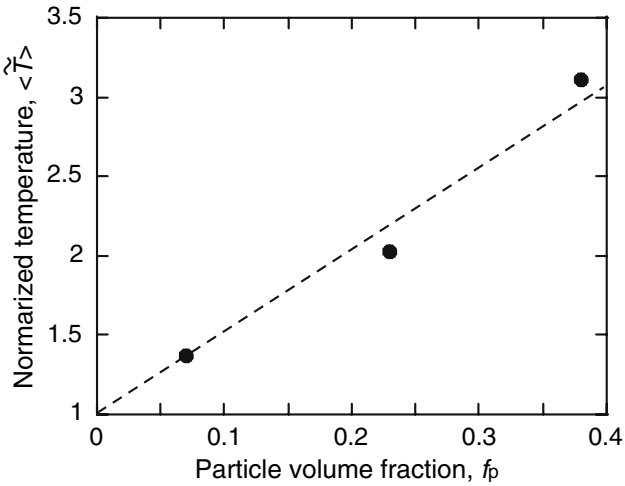

Fig. 6 Relationship between normalized temperature, $\langle T \rangle$, and particle volume fraction, f_p

$$\langle \tilde{T} \rangle = \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} T_c \mathrm{d}t. \tag{3}$$

with $t_1 = 400$ s and $t_2 = 600$ s. The plots could be assumed to have a linear relationship and this relation indicates that the absorption potential is qualitatively increased with a total amount of H_2O in the composite, f_p. The dielectric constant, ε, is expressed as a summation of real term, ε_1, and imaginary term, ε_2 [15],

$$\varepsilon = \varepsilon_1 - i\varepsilon_2. \tag{4}$$

The imaginary part, ε_2, represents the dielectric loss. The dielectric constant of H_2O at a frequency of 2.45 GHz is $\varepsilon_1 = 9.5$ and $\varepsilon_2 = 76$ [11], such a high value of dielectric loss of H_2O originates from the kinetic energy motion of electric dipole moments. Dielectric loss of SiO_2 and paraffin is negligible ($\varepsilon_2 \sim 0$ [1, 16]) and sufficiently smaller than that of H_2O. Thus, H_2O plays a major contribution to the absorption and it is reasonable that the total amount of electromagnetic wave absorption becomes larger with the increase of H_2O volume, f_p, in the composites. Detailed discussion on the absorption mechanism is beyond the scope of this paper and will be reported by a separate paper [17]. The present experimental result shows that observation of the temperature change is an effective way to observe the interaction behavior of an electromagnetic wave and absorbing materials.

A new experimental tool for direct observation of electromagnetic wave absorption behavior has been proposed. The tool is applied to the electromagnetic wave absorbing potential of H_2O-filled thin SiO_2 shell sphere particle-dispersed paraffin matrix composites. Results clearly demonstrate the potential for the evaluation of electromagnetic wave absorption. More detailed experiments using various kinds of materials are needed to prove the applicability of the present experimental procedure. However, it is clear that the method seems attractive especially for the development of electromagnetic wave absorbing materials because the procedure directly shows evidence of the absorption.

References

1. Neelakanta PS (1995) Handbook of Electromagnetic Materials, CRC Press, 1995, 491–509
2. Lynch AC (1974) IEEE Trans Inst Measure 23:425–431
3. Kadaba PK (1984) IEEE Trans Inst Measure 33:159–161
4. Ghodgaonkar DK, Varadan VV, Varadan VK (1989) IEEE Trans Inst Measure 37:789–793
5. Ghodgaonkar DK, Varadan VV, Varadan VK (1990) IEEE Trans Inst Measure 39:387–394
6. Varadan VV, Ro R, Varadan VK (1994) Radio Sci 29:9–22
7. Annadurai P, Mallick AK, Tripathy DK (2002) J Appl Polym Sci 83:145–150
8. Das NC, Khastgir D, Chaki TK, Chakraborty A (2002) J Elastomers Plastics 34:199–223
9. Lu G, Li X, Jiang H (1996) Compos Sci Tech 56:193–200
10. Kagawa Y, Imahashi Y, Iba H, Naganuma T, Matsumura K (2003) J Mater Sci Lett 22:159–161
11. Ellison WJ, Lamkaouchi K, Moreau JM (1996) J Mol Liquid 69:171–279
12. Washin Kagaku Co., *Technical Date sheet*, Shizuoka, Japan
13. Atkins P, de Paula J (2002) Phys Chem, 7th ed. Oxford University Press, p 1073
14. Munz D, Fett T (1999) Ceramics. Springer-Verlag, 15
15. von Hippel A (1995) Dielectrics and waves. Artech House Publishers, p 4
16. Fatykhov MA (2002) High Temp 40:802–809
17. Matsumura K, Kagawa Y, in preparation