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Theoretical study of the interface effect on the electromagnetic wave absorbing characteristics

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ABSTRACT

The influence of interface effect between inclusion particles and matrix in composite on electromagnetic wave absorbing characteristics has been investigated. Firstly, an effective permittivity model of composite with interfacial shell is established. And then the formula for the effective permittivity and permeability of composite with interface is derived based on the effective medium theory. According to the proposed formula and transmission line theory, the influence of the interface effect on the electromagnetic wave absorption characteristics is discussed. The size effect of the inclusion on the reflection loss of absorbing composite is also studied. All these results indicate that the interface effect of inclusion particle should be considered in design and application of the electromagnetic wave absorbing composites when the size of the filler particles is in micron range.

1. Introduction

Electromagnetic wave absorbing functional materials not only play a significant role in military stealth technology field [1,2], but also widely applied in commercial devices [3,4]. Whether the absorbing material can achieve excellent absorbing ability or not, the selection of absorbent is the most important. Filling electromagnetic composites with micro-scale or nano-scale granules is considered as one of the most effective methods to enhance the absorbing capability of composites. Along with decreasing the size of filler particles, the interfacial layer between inclusion particles and matrix will give rise to very important impact to the electromagnetic properties [5–7]. Although the effective electromagnetic parameters of composites have been predicted and analyzed in existent literature [8–10], the interface effect, generated by the interfacial layer, on electromagnetic wave absorbing properties and the related scale characteristics are still short of investigation. Therefore, this paper presents theoretical researches on the influence of interface effect on the absorbing properties of electromagnetic composites. The results indicate that relationship between the reflection loss and interface exhibits the size effect obviously. Once the size of filler particles in composite is small enough to micron size, the interface effect must be taken into account.

2. Theory for microwave absorber

The reflection loss (RL) is an important index to describe the absorbing characteristics of materials. On the basis of the transmission line theory [11], the reflection loss of single-layer absorbing material can be calculated by the following expression:

$$R = 20\lg\left|\frac{Z_{in}-Z_0}{Z_{in}+Z_0}\right| \tag{1}$$

where $Z_0=(\mu_0/\varepsilon_0)^{1/2}=120\pi$ is the impedance of air and Z_{in} the input impedance of absorber.

$$Z_{in} = Z_0\left(\frac{\mu_r}{\varepsilon_r}\right)^{1/2}\tanh\left[j\frac{2\pi fd}{c}(\mu_r\varepsilon_r)^{1/2}\right] \tag{2}$$

where f is the frequency of the electromagnetic wave, d the thickness of an absorber, c the velocity of light in vacuum, $\varepsilon_r=\varepsilon_r'-j\varepsilon_r''$ the relative permittivity and $\mu_r=\mu_r'-j\mu_r''$ the relative permeability.

As seen from Eqs. (1) and (2), reflection loss depends on physical parameters of materials, such as the effective permittivity, the effective permeability, thickness of composite as well as the incident electromagnetic wave frequency. Therefore, it is important to predict the electromagnetic parameters of composite precisely.

3. Effective theory of composites with core-shell particles

3.1. Equivalency to core-shell spherical particles

An equivalent method, combining the interfacial layer and the filler particle as a "complex particle", is adopted to investigate the influence of interfacial layer on effective permittivity. Here a model with three-phase components is established. For simplicity, the permittivity is assumed to be unchangeable inside the interfacial layer. Usually, the scattered particles can be considered as spherical particles. It is supposed that R_1 and R_2 are the radius

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of core particle with permittivity ε_1 and interfacial shell with permittivity ε_2 of the complex particle, respectively. The thickness of interfacial layer is $t=R_2-R_1$, and the permittivity of matrix is ε_m. Under quasi-static approximation and the incident wavelength much larger than the particle size, when an electromagnetic field E_0 is incident perpendicularly to the complex particle, the electric potential in each component in composite is given by the Laplace equation:

$$\phi_c = -AE_0 r\cos\theta, \quad r<R_1 \tag{3}$$

$$\phi_s = -E_0\left[Br-\frac{CR_1^3}{r^2}\right]\cos\theta, \quad R_1<r<R_2 \tag{4}$$

$$\phi_m = -E_0\left[r-\frac{DR_2^3}{r^2}\right]\cos\theta, \quad r>R_2 \tag{5}$$

Coefficients *A*, *B*, *C* and *D* are determined by the boundary conditions. As shown in Eq. (5), the outer electric potential contains two parts: one part is the contribution of outfield, and the second can be considered as the contribution of electrical dipole moment of medium sphere. The overall electrical dipole moment of the spherical particle with interfacial shell is calculated through the electric potential generated by the electrical dipole moment in the space [12].

$$\vec{\boldsymbol{p}} = \frac{\gamma\varepsilon_1-\varepsilon_m}{\gamma\varepsilon_1+2\varepsilon_m}\boldsymbol{4}\pi\varepsilon_m R_2^3\vec{\boldsymbol{E}}_{\boldsymbol{0}} \tag{6}$$

$$\gamma = \frac{\beta(1+2\beta)+2\alpha\beta(1-\beta)}{(1+2\beta)-\alpha(1-\beta)} \tag{7}$$

where γ and $\alpha=R_1^3/R_2^3$ are called equivalent coefficient and structure parameter, respectively, and $\beta=\varepsilon_2/\varepsilon_1$.

Solid spherical particles with permittivity ε_1 and radius R_1 embedding in the same homogeneous matrix can be made up of another composite. Illuminated perpendicularly by electromagnetic field $\vec{\boldsymbol{E}}_{\boldsymbol{0}}$, the overall electrical dipole moment of solid particle is calculated with the following formula:

$$\vec{\boldsymbol{p}} = \frac{\varepsilon_1-\varepsilon_m}{\varepsilon_1+2\varepsilon_m}\boldsymbol{4}\pi\varepsilon_m R_1^3\vec{\boldsymbol{E}}_{\boldsymbol{0}} \tag{8}$$

In comparison of Eq. (6) with Eq. (8), it is shown that the difference in the two equations is just replacing $\gamma\varepsilon_1$ and R_2 in Eq. (6) to ε_1 and R_1 in Eq. (8). Therefore a spherical particle with interface equates another spherical particle without interface, and this leads to a result that the composite system can be replaced by solid sphere with equivalent permittivity $\gamma\varepsilon_1$ and equivalent radius R_2 mixed with the same matrix.

3.2. Effective permittivity of composite with core-shell particles

There are numerous mixture equations that are used to calculate effective permittivity of two-phase composites, such as the Clausius–Mossotti equation, the Maxwell–Garnett equation, the Bruggeman equation and the QCA-CP equation. These equations can be represented in the following form [9,13]:

$$\frac{\varepsilon_{eff}-\varepsilon_m}{\varepsilon_{eff}+2\varepsilon_m+\nu(\varepsilon_{eff}-\varepsilon_m)} = V\frac{\varepsilon_i-\varepsilon_m}{\varepsilon_i+2\varepsilon_m+\nu(\varepsilon_{eff}-\varepsilon_m)} \tag{9}$$

where ε_m, ε_i and ε_{eff} is the permittivity of matrix, filler particles and mixture, respectively. *V* is the volume fraction of the inclusion particle. The parameter ν depends on the particle density and on the difference between matrix and particle permittivities. With different parameter ν, Eq. (9) exhibits different well-known equations. $\nu=0$ and $\nu=2$ give the Maxwell–Garnett equation and the Bruggeman equation, respectively, and the QCA-CP equation is the case $\nu=3$. The latter two have been widely used to describe the microwave properties of magnetic mixtures [14].

The following step is to investigate the composite system composed of core-shell particles mixed with linear matrix randomly. It is still postulated that R_1 and R_2 are the radius of core with permittivity ε_1 and shell with permittivity ε_2 of the complex particle, respectively, and the permittivity of matrix is ε_m. According to the equivalent method, the particle with interfacial layer can be replaced by solid particle with equivalent permittivity $\gamma\varepsilon_1$ and equivalent radius R_2. So only by substituting Eq. (7) into Eq. (9), we can get the equation for effective permittivity based on the Bruggeman model, which can accurately describe the microwave properties of the ferrite-medium mixtures [14].

$$V'\frac{\gamma\varepsilon_1-\varepsilon_{eff}}{\gamma\varepsilon_1+2\varepsilon_{eff}}+(1-V')\frac{\varepsilon_m-\varepsilon_{eff}}{\varepsilon_m+2\varepsilon_{eff}}=0 \tag{10}$$

where $V'=V/\alpha$, and *V* is the volume fraction of granular core. The modified formula is universal and available for calculating effective permittivity of composite system composed of coated spherical inclusions embedded in homogeneous matrix randomly. The theoretical results on the effective permittivity are in agreement with the experimental data in the literature [15].

Due to the symmetry of electromagnetic problem, the effective permeability can be obtained by replacing permittivity ε with permeability μ in the above equations. Combining Eqs. (1) and (2), Eqs. (7) and (10), we can explore relationship between the interface effect and absorbing characteristics of composites.

4. Results and discussion

Fig. 1 presents the relationship between the effective permittivity and the volume fraction of filler particle when considering interface effect. It is given that the permittivity of filler particle with radius *R* is $\varepsilon_1=20$, and that of the interfacial layer with thickness $t=2$ nm is ε_2, $\beta=\varepsilon_2/\varepsilon_1$. As shown in Fig. 1, when the characteristic scale of absorbent particles is far larger than that of interfacial layer, the influence of interfacial layer on the effective permittivity is almost negligible; when the characteristic scale of interfacial layer is close to the characteristic scale of absorbent particles, the interfacial layer puts obvious impact to the effective permittivity, especially for higher content of the nuclear particles. And the specific value β can change the trend of effective permittivity (shown in Fig. 1(b) and (c)). when $\beta<0.1$, the permittivity of interfacial layer is much smaller than that of the inclusion, which leads to the decrease in effective permittivity relative to that without considering the interface effect. When $\beta>0.1$, the permittivity of interfacial layer is close to that of the inclusion. The polarization between the particle and the matrix is strengthened, which results in the increase of effective permittivity relative to that without considering the interface effect.

To investigate the influence of the interfacial layer on the absorbing properties of composite, several simulations were carried out based on Eq. (10) and the transmission line theory. In following numerical calculation and analysis, materials and their related electromagnetic parameters are given in the literature [16]. Namely, the complex permittivity and permeability of epoxy resin matrix are $\varepsilon_m=3.19-j0.19$ and $\mu_m=1-j0$, and that of absorbent LDT-10 iron carbonyl are $\varepsilon_1=117.5-j18.32$ and $\mu_1=2.75-j6.48$, respectively. The two components seems to be independent of frequency at the radar microwave band [17]. For the metal/insulator composite, on condition that the conductivity of filler particles is much larger than that of the matrix,