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Study on absorbing property of rare earth transitionmetal intermetallic compound/epoxy resin composites

The complex permeability and permittivity spectra of transitionmetal intermetallic compound/epoxy resin composites was measured, which indicates high complex permeability of the composites in high frequency range. Both complex permeability and permittivity of the composites increase with increase of the volume fraction of ransitionmetal intermetallic compound. According to the complex permeability and permittivity spectra of transitionmetal intermetallic compound/resin composite, the single-layer plate absorber wear prepared. The test result on the reflection loss shows that the single-layer coating material has minimum reflection loss -24dB and effective bandwidth 6.4 GHz within 8-18 GHz with volume fraction of 23% for absorbent powder and 1.4mm thickness of the absorbing layer.

Key words: Absorbing materials; permeability; reflection loss.

1. Introduction

Microwave absorbing coating material is mainly composed of microwave absorbent and the resin matrix. Common attention has been paid to the microwave absorbing coating material [1-4], since it has many advantages such as easy preparation and is applicable to devices with various shapes. As the development of anti-stealth technology, it is necessary to exploit new kind of microwave absorbing coating material with broad bandwidth, strong absorbing, thin thickness and low surface density [5-9].

It is reported that the rare earth transitionmetal intermetallic compounds with in-plane anisotropy has higher permeability at high frequency compared to traditional Z-hexaferrite. And the rare earth transitionmetal intermetallic compounds may have better microwave absorbing property because it can reduce eddy-current loss effectively, which indicate that it will be good microwave absorbing material [10]. The epoxy resin is usually used as the matrix of the absorbing coating materials due to its good performance of physical properties such as adhesive force. This paper investigated the electromagnetic spectrum characteristics and microwave absorbing properties of the composites composed of a kind of rare earth transitionmetal intermetallic compounds (that is $Ce_2(Co_{0.3}Fe_{0.7})_{17}$) and epoxy resin.

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2. Experiment

2.1 Materials

The diameter of the rare earth transitionmetal intermetallic compounds particles $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ was 10-50 microns and the particles were of in-plain anisotropy. Epoxy resin (E44) and polyamide (650) were used as the matrix resin. Square aluminum plate with 18 centimeters in length was prepared for the coating material.

2.2 Preparation of coaxial specimens

Epoxy resin and polyamide with mass ratio 1:1 were firstly weighed out and then put into the crucible. The n-butyl alcohol was added into the matrix resin to dissolve the epoxy resin and polyamide with an ultrasonic cleaning facility (KQ218) for about 5 minutes. Then, the prepared absorbent was added into the crucible, and the ultrasonic cleaning facility (KQ218) was used to provide a continuous ultrasonic dispersion for about 1.5 hour. After the process of ultrasonic dispersion, the absorbent/resin compound was extracted from the crucible and cut into granular particles. The particles were then put into the coaxial mold (inner diameter 3.04 mm, external diameter 7.00 mm) and compressed by tablet compressing machine (model for FW- 4) under the pressure of 2MPa for 8 hours.

2.3 Preparation of coating specimens

The absorbent was added into epoxy resin and polyamide for dispersion respectively to prepare two-component coating material. Each of the components was dispersed with high-speed grinding machine (SKL-FS400). For epoxy resin component, epoxy resin was firstly added into the tank, following with the absorber and zirconium bead, with a low stirring speed (< 500 r/min). The stirring speed was then gradually raised to 4000 r/min, and at the same time, the mixed solvent of xylene and n-butyl alcohol (mass ratio of 5:1) was added into the tank. After the dispersion process for 4 hours, zirconium beads were washed out using the same mixed solvent. The same dispersion process was for polyamide components. The spraying process was adopted to prepare coating specimens using the two dispersed components. Finally, the coating specimens were solidified at room temperature.

2.4 The test of reflection loss

The curve of reflection loss was tested in the frequency range of 8-18GHz using bow testing method. Dielectric constant $\varepsilon_r\left(\varepsilon_r = \varepsilon_r' - j\varepsilon_r''\right)$ and permeability $\mu_r\left(\mu_r = \mu_r' - j\mu_r''\right)$ of the coaxial specimens were tested by vector network analysis method in the frequency range of 0.1-18 GHz.

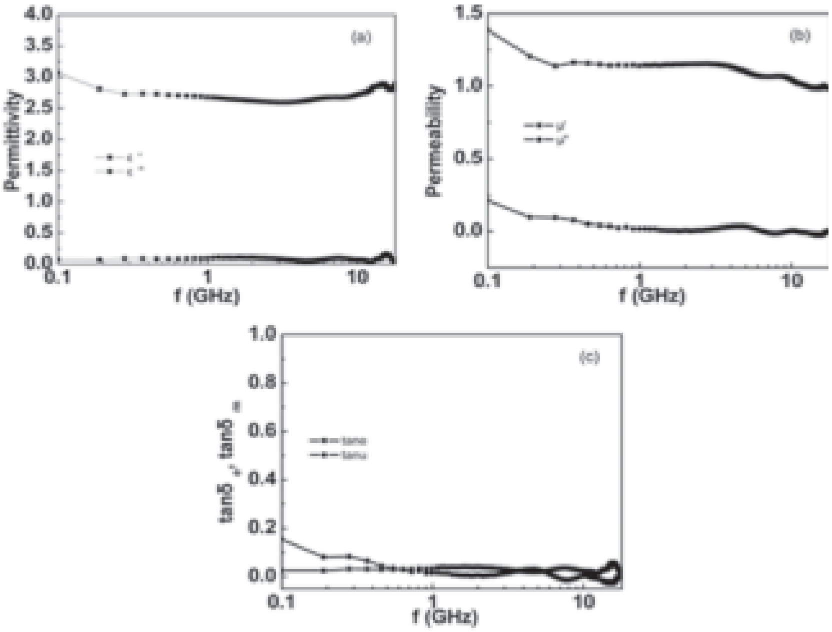

Fig.1 Frequency dependences of relative permittivity, relative permeability and tan δ of epoxy resin material

3. Results and discussion

3.1 Electromagnetic spectrum of the resin matrix

It is necessary to investigate the electromagnetic property of the matrix if we want to study the electromagnetic properties and absorbing characteristics of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/resin composites. Firstly, the pure resin coaxial specimens without absorbent were prepared, in which the mass ratio of epoxy resin (E44) versus polyamide (650) was 1:1, and the electromagnetic spectrums were tested in the frequency range of 0.1-18 GHz. The frequency dependences of relative permittivity, relative permeability and of the resin matrix used in this paper are displayed in Fig.1. The loss angle tangent value is defined as:

$$\tan\delta_e = \frac{\varepsilon''}{\varepsilon'} \quad \text{... (1)}$$

$$\tan\delta_m = \frac{\mu''}{\mu'} \quad \text{... (2)}$$

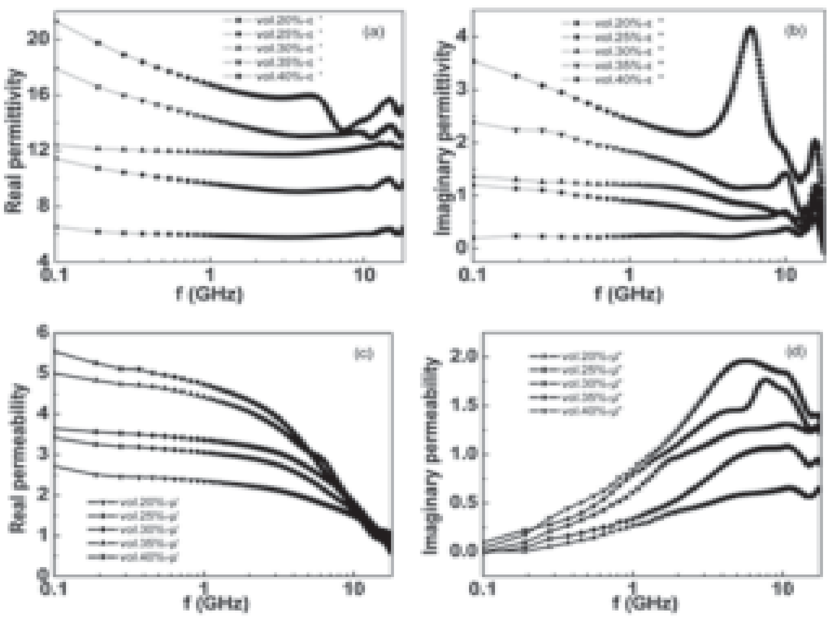

Fig.2 Frequency dependences of relative permittivity, relative permeability of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/resin composites with different volume concentrations

where tan δ_e and tan δ_m are the loss angle tangent values obtained from relative permittivity and relative permeability respectively, which represent the microwave depletions of the materials.

It can be seen from Fig.1 that the imaginary part of permittivity, imaginary part of permeability, electric tangent of the loss angle tan δ_e and magnetic tangent of the loss angle tan δ_m are close to 0, and at the same time the real part of permittivity and real part of permeability are very small. The resin matrix composed of epoxy resin and polyamide can be regarded as a kind of material with good permeability to microwaves. The epoxy resin is just used to bond and disperse the absorbent, while the electromagnetic properties are mainly reflected by the absorbent composition for $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/resin composites.

3.2 Electromagnetic spectrum of the $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/epoxy resin composites

The relative permittivity and relative permeability of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/epoxy resin composites will be influenced by the volume concentration of absorbent and also the dispersion of the absorbent in matrix. To study the electromagnetic spectrum of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/epoxy resin composites with different $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentrations, the coaxial specimens with five $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentrations (20%, 25%, 30%, 35% and 40% respectively) were prepared and tested. The results of the relative permittivity and relative permeability of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/epoxy resin composites are shown in Fig.2.

Fig.2 shows that the real and imaginary part of both permittivity and permeability of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/epoxy resin composites increase with increase of the volume concentration of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ particles. The real part of permittivity is less than 22 and the imaginary part of permeability is bigger than 2 when the volume concentration of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ particles reach 2. So, the real part of permittivity of the composites will not be too high at a high imaginary part of permeability to avoid impedance mismatch. It can be seen from Fig.2 that the peak frequency of the imaginary part of permeability move towards the low-frequency with increase of the volume concentration of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ particles, which indicates a tendency of resonant frequency also move towards low-frequency with increase of volume concentration of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ particles.

3.3 Influence of the $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration on reflection loss

According to the theory of transmission lines [11-14], based on the relative permittivity and relative permeability in Fig.2 the reflection loss of single-layer plate absorber can be calculated from the following equations:

$$R = 20\lg\left|\frac{Z_{in}(1)-Z_0}{Z_{in}(1)+Z_0}\right| = 20\lg\left|\frac{\eta_{in}(1)-1}{\eta_{in}(1)+1}\right| \quad \ldots \quad (3)$$

$$\eta_{in}(1) = \eta_1 tgh(jk_1 d_1) = \sqrt{\frac{\mu_{r1}}{\varepsilon_{r1}}}tgh\left(j\frac{2\pi f\sqrt{\varepsilon_{r1}\mu_{r1}}}{c}d_1\right) \quad \ldots \quad (4)$$

where c is the velocity of light; f is the frequency of electromagnetic wave; d_1 is the thickness of absorbing layer; ε_{r1} and μ_{r1} are the imaginary permittivity and imaginary permeability respectively.

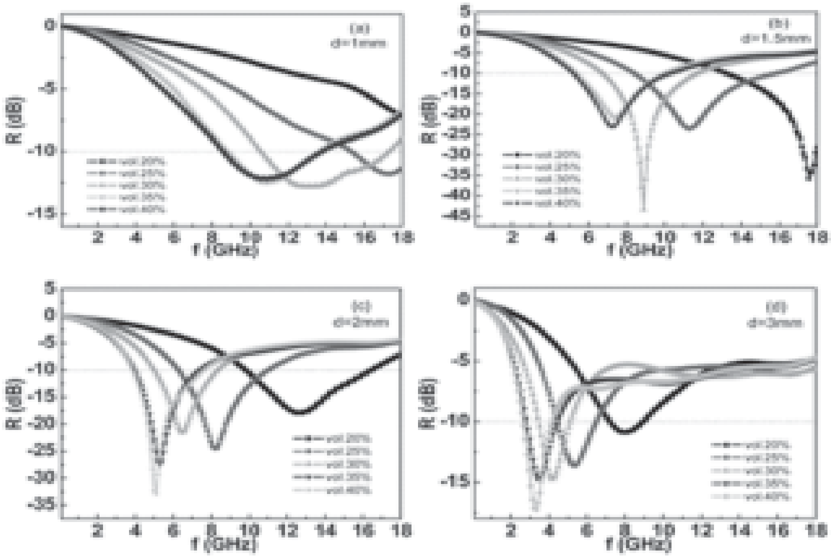

Fig.3 Frequency dependences of reflection loss of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/resin single-layer plate absorber with different $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentrations at a giving thickness

Based on the obtained relative permittivity and relative permeability of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/ resin composites with different volume concentrations (20%,25%,30%,35%,40%) in Fig.2, the reflection loss can be calculated from equation (3) and equation (4) with a certain thickness, and the results are displayed in Fig.3 and Table 1.

Table 1: Minimum reflection loss (MRL) and peak frequency (PF) of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/ resin single-layer plate absorber with different $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentrations at a giving thickness

Thickness	MRL and PF	$Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration				
		20%	25%	30%	35%	40%
1mm	MRL (dB)	-	-11.8	-12.8	-12.4	-12.2
	PF (GHz)	-	17.3	12.9	10.9	10.6
1.5mm	MRL (dB)	-35.8	-23.6	-43.6	-20.9	-23.1
	PF (GHz)	17.6	11.3	8.9	7.4	7.3
2mm	MRL (dB)	-18.0	-24.5	-21.6	-27.4	-32.9
	PF (GHz)	12.8	8.2	6.5	5.3	5.1
3mm	MRL (dB)	-10.9	-13.6	-14.7	-14.8	-17.2
	PF (GHz)	8.0	5.3	4.2	3.5	3.3

It can be seen from Fig.3 and Table 1 that the peak frequencies corresponding to minimum reflection loss shift to the lower frequencies with a giving thickness. According to the interface reflection model for single-layer plate absorber [15-16], the peak frequency f_m and a quarter of thickness$d_{1/4}$ of the absorbing layer can be related as following equation:

$$d_{1/4} = n\left(\frac{1}{4}\frac{c}{f_m\sqrt{|\mu_r(f_m)||\varepsilon_r(f_m)|}}\right)(n = 1,3.5,\ldots) \quad \ldots \quad (5)$$

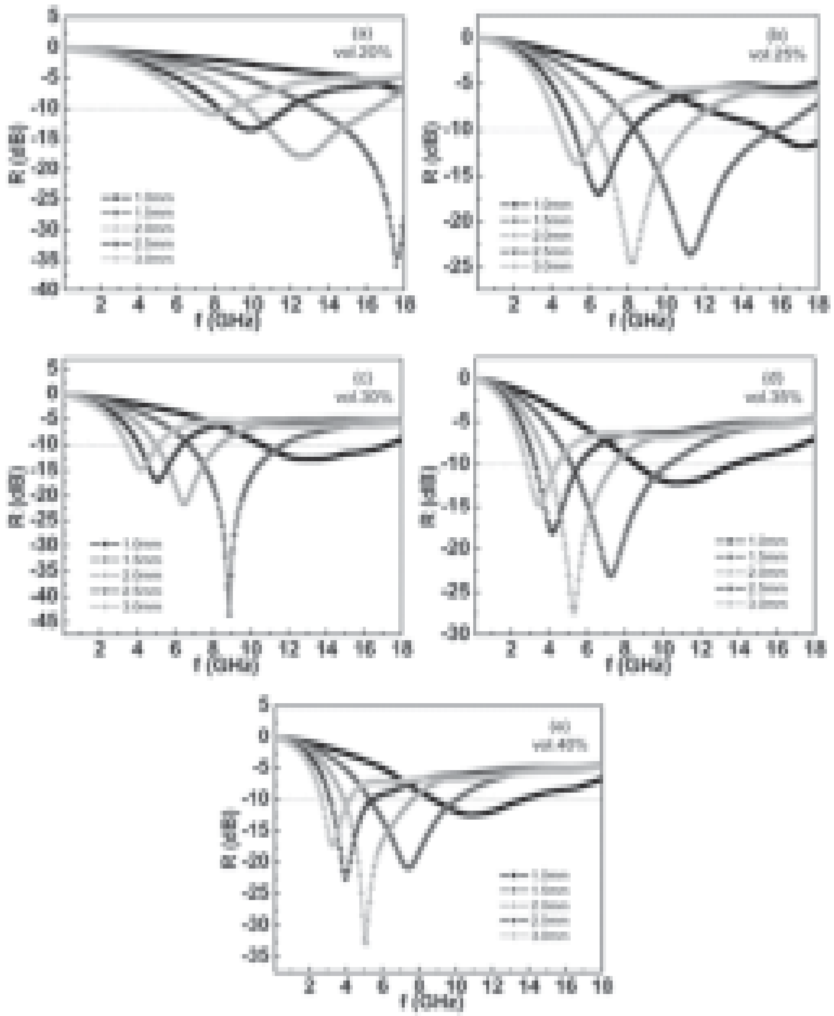

Fig.4 Frequency dependences of reflectivity of different thicknesses at a giving volume concentration

which indicates a reduction of the peak frequency f_m with increase of imaginary permittivity ε_{r1} and imaginary permeability μ_{r1} at the giving a quarter of thickness $d_{1/4}$. The conclusion obtained from equation (5) consists with the results displayed in Fig.3 and Table 1, since the imaginary part of both permittivity and permeability of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/ epoxy resin composites increase with increase of the volume concentration of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ particles in Fig.2.

As the results shown in Fig.3 and Table 1, the volume concentration of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ particles should be in the range of 25% to 30% at the given thickness of 1mm in order to prepare single-layer plate absorber with good microwave absorbing performance in 8-18GHz band. While the volume concentration of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ particles should be in the range of 25% to 30% if the thickness is set as 1.5mm. We can conclude that the a higher volume concentration of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ particles is needed to prepare a single-layer plate absorber with good microwave absorbing performance in 8-18GHz band if a thinner absorbing layer is expected, and under this circumstance the surface density of the absorbing layer may be increased. However, the thickness of the absorbing layer should be increase if reduce the volume concentration of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ particles, which may also increase the surface density of the absorbing layer. The further experimental on coating specimens should be conducted to obtain the optimum volume concentration of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ and thickness in order to prepare single-layer plate absorber with good microwave absorbing performance and relatively low surface density.

3.4 Influence of the thickness on reflection loss

Based on the obtained relative permittivity and relative permeability of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/ resin composites with different volume concentrations (20%,25%,30%,35%,40%) in Fig.2, the reflection loss can also be calculated from equation (3) and equation (4) with different thickness at a given volume concentration, and the results are displayed in Fig.4.

Fig.4 indicates that the peak frequency on the reflection loss curve shift to lower frequencies with increase of the thickness for each of the $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration, which can also be explained by the interface reflection model. The interface reflection model points out that, for single-layer plate absorber, the peak frequency of reflection loss curve is the frequency corresponding to the wavelength which is four times of the thickness of absorbing layer. The wavelength corresponding to peak frequency will increase with increase of the thickness, and on the contrary, the peak frequency will decrease, which indicates the shifting of peak frequency to lower frequency with increase of thickness. It can be seen from Fig.4 that, at a giving $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration, the minimum reflection loss will decrease firstly and then increase with increase of thickness. There is an optimum thickness, with which the peak reflection loss is lower than that with other thicknesses. According to the interface reflection model, there exists an optimum thickness with which the phase difference of the reflected electromagnetic waves on the front- interface and the back-interface is π, while the amplitudes of these two electromagnetic waves are the same. With this optimum thickness and under peak frequency, the reflected electromagnetic waves on the front-interface and the back-interface will interfere destructively inducing a complete absorbing. However, the complete absorbing will not occur

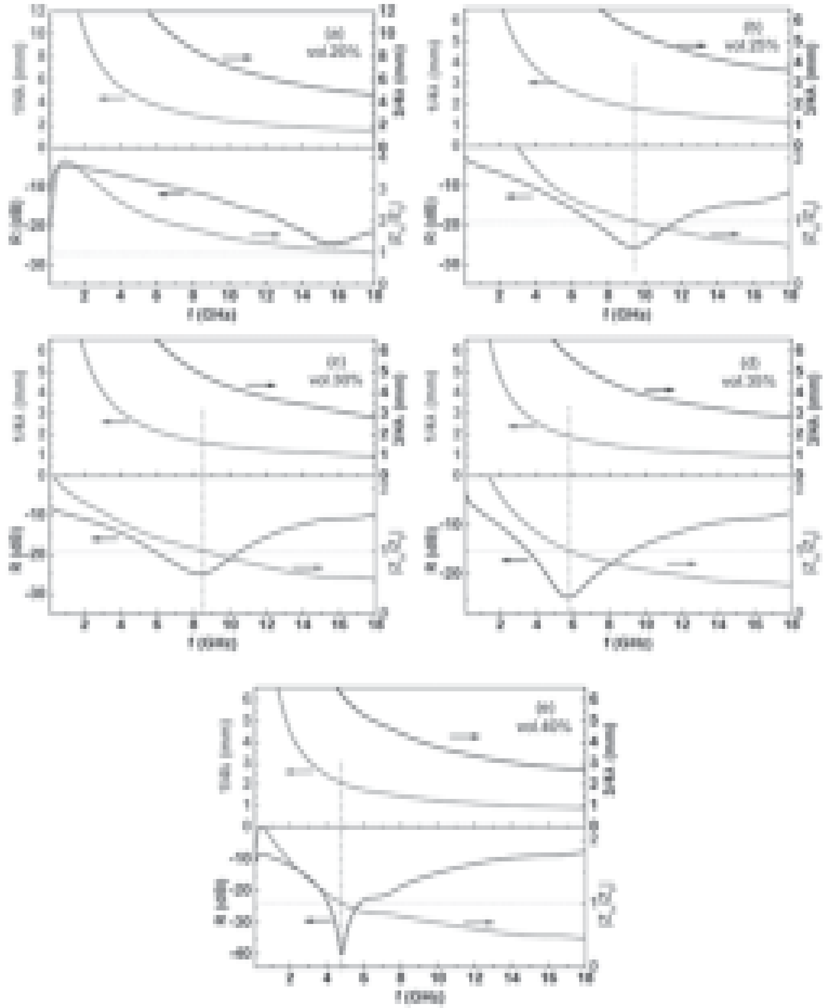

Fig.5 Frequency dependence of (1/4)γ, (3 /4)γ, normalized input impedance and minimum reflectivity at the (1/4)γ thickness of the $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/resin composites

epoxy resin composites are shown in Fig.5, which includes the frequency dependence of (1/4)γ, (3/4)γ, normalized input impedance and minimum reflection loss at the (1/4)γ thickness of the composite in a subfigure. And $|Z_m/Z_0|$ and γ represent normalized input impedance and wavelength at a certain frequency in these figures.

It can be seen from Fig.5 that the peak value of reflection loss curve will reach the minimum value when the normalized input impedance is equal to 1, and under this circumstance the impedance is fully matched and has strongest absorption to microwave. Fig.5 illustrates that the completely impedance matching point (the intersection at the curve of normalized input impedance and the line of $|Z_m/Z_0|=1$), shifts to lower frequency with increase of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration. From Fig.5, the completely impedance matching point is in frequency of 8.5GHz with the $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration 30%, while the completely impedance matching point is out of frequency band 8-18GHz with $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration of 35% and 40%. Thus the $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration should be ranged between 20% and 30% from the aspect of impedance matching in order to obtain an absorber with strong absorption and broad bandwidth in 8-18 GHz.

TABLE 2: TECHNICAL DATA OF THE SINGLE-LAYER COATING SPECIMENS

Vol.	Thickness (mm)	MRL (dB)	PF (GHz)	Effective bandwidth (GHz)	Surface density (kg/m^2)
20%	1.6	-12.8	12.8	6.1	3.48
23%	1.4	-24.3	13.1	6.4	3.41
25%	1.3	-28.1	15.9	5.8	3.39
28%	1.2	-14.2	11.2	6.2	3.37
30%	1.0	-15.5	9.8	4.2	3.28

with other thicknesses due to difference in amplitudes, even though the reflected electromagnetic waves on the front-interface and the back-interface will also interfere destructively under peak frequency.

3.5 REFLECTION LOSS CHARACTERISTIC CURVE OF $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/EPOXY RESIN COMPOSITES

In order to fully display the microwave reflection loss characteristic for $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/ epoxy resin composites, the reflection loss characteristic curve of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/

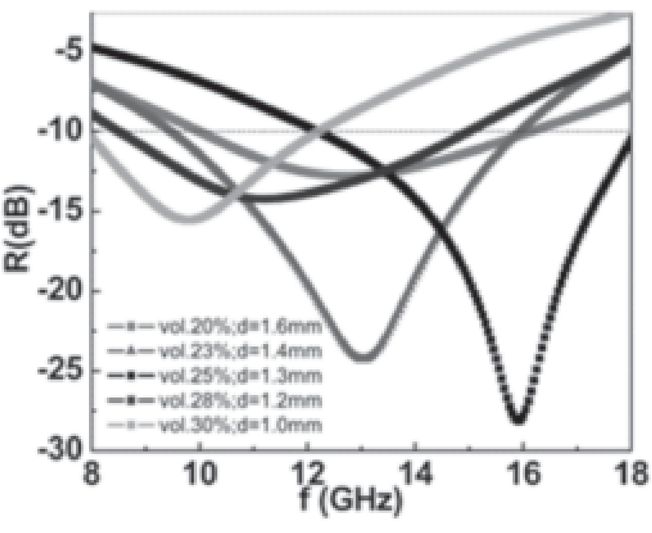

Fig.6 Frequency dependences of reflection loss for the $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/ epoxy resin single-layer coating materials with different volume concentrations (20%, 23%, 25%, 28%, 30%)

3.6 Reflection loss of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/epoxy resin coating materials

According to the test results and discussion above, the $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration should be ranged between 20% and 30% from the aspect of impedance matching in order to obtain an absorber with strong absorption and broad bandwidth in 8-18GHz. So, the $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/epoxy resin single-layer coating materials with five $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentrations (20%, 23%, 25%, 28%, 30%) were prepared on aluminum plate with 18 centimeters in length. The results of reflection loss are displayed in Fig.6 and Table 2.

It can be seen from Fig.6 and Table 2 that the single-layer coating specimen with $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration 23% has the largest effective bandwidth (in which the reflection loss is less than -10 dB) 6.4 GHz, and the minimum value of reflection loss, thickness of absorbing layer and surface density are -24 dB, 1.4 mm and 3.39 kg/m^2 respectively, indicating a strong absorption, thin thickness and relatively wide effective bandwidth characteristic.

4. Conclusions

(1) The real part of permittivity of the $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/epoxy resin composites will not be too high at a high imaginary part of permeability so that can avoid impedance mismatch to same extent.

(2) The peak frequencies corresponding to minimum reflection loss shift to the lower frequencies with increase of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration at a giving thickness. And also the peak frequencies corresponding to minimum reflection loss will shift to the lower frequencies with increase of thickness at a giving $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration, which can be explained by the interface reflection model.

(3) The single-layer coating specimen with $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration 23% has effective bandwidth, minimum value of reflection loss, thickness of absorbing layer and surface density of 6.4 GHz, -24 dB, 1.4 mm and 3.39 kg/m^2 respectively, indicating a strong absorption, thin thickness and relatively wide effective bandwidth characteristic.

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References

1. Folgueras, L. C., Alves, M. A. and Rezende, M. C. (2014): *Material Research. Suppl.* 1, 17 (2014).
2. Panwar, R., Puthucheri, S., Agarwala, V. and Singh, D. (2015): *Microwave Theory and Techniques*. 8, 63 (2015).
3. Seo, I. S., Chin, W. S. and Dai, G. L. (2004): *Composite Structures*. S 1-4, 66 (2004).
4. Xiong, G. X., Xu, L. L., Deng, M., Huang, H. Q. and Tang, M. S. (2005): *Journal of Functional Materials & Devices*. 1, 11 (2005).
5. Oh, J. H., Oh, K. S., Kim, C. G. and Hong, C. S. (2004): *Composites Part B Engineering*. 1, 35 (2004).
6. Yusoff, A. N. and Abdullah, M. H. (2004): *Journal of Magnetism & Magnetic Materials*. 2, 269 (2004).
7. Liu, X., Pan, S., Cheng, L., Li, C., Mo, H., and Zhou, H. (2015): *Rare Metal Materials and Engineering*. 9, 44 (2015).
8. Zhang, Z. Q., Wei, J. Q., Yang, W., Qiao, L., Wang, T. and Li, F. (2011): *Physica B Condensed Matter*. 20, 406 (2011).
9. Han, R., Qiao, L., Wang, T. and Li, F. S. (2011): *Journal of Alloys & Compounds*. 6, 509 (2011).
10. Li, F. S., Yi, H. B., Zuo, W. L. and Liu, X. (2010): Microwave magnetic properties of 2:17 Rare earth-3d transitionmetallic intermetallic compounds with planar magnetic anisotropy. CN Patent 201010230672.3, Nov 10 (2010).
11. Liu, X., Wu, N., Cui, C., Li, Y., Zhou, P. and Bi, N. (2015): *Materials Letters*. 15, 149 (2015).
12. Liu, Y., Liu, X. and Wang, X. (2014): *Journal of Alloys and Compounds*. 25, 584 (2014).
13. Wang, Y., Luo, F., Zhou, W. and Zhu, D. (2014): *Ceramics International*. 7, 40 (2014).
14. Zou, T. C., Zhao, N. Q., Shi, C. S. and Li, J. J. (2005): *Functional materials*. 7, 36 (2005).
15. Wei, J. Q., Zhang, Z. Q., Wang, B., Wang, T. and Li, F. (2010): *Journal of Applied Physics*. 12, 108 (2010).
16. Han, R., Gong, L. Q., Wang, T., Qiao, L. and Li, F. (2012): *Materials Chemistry Physics*. 3,131 (2012).

APPLICATION OF GEO-MINING AND TECHNO-ECONOMIC PARAMETERS FOR OPTIMUM SELECTION OF STOPING METHOD FOR UNDERGROUND METALLIFEROUS MINES

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17. Amir Azadeh , M. Osanloo, M. Ataei, 2010, "A new approach to mining method selection based on modifying the Nicholas technique "Applied Soft Computing ,Vol.10, pp. 1040–1061.
18. FarhadSamimiNamin, K.Shahriar, AtacBascetin, S.H. Ghodsypour, 2009, "Practical applications from decision-making techniques for selection of suitable mining method in Iran"
19. Dennis Krantz , Tim Scott, "Hard-Rock Mining: Method Selection Summary", Chapter 21.3,pp 1850-1853.
20. F. SamimiNamin, K.Shahriar, A.Bascetin,2011 " Environmental impact assessment of mining activities. A new approach for mining methods selection" The Journal of The Southern African Institute of Mining and Metallurgy, Vol. 27, pp. 113-143.
21. StanujkicDragisa, Bogdanovic Dejan, 2006 "Possibility of Application of Intelligent Systems For Selection of Mining Method" Underground Mining Engineering, Vol. 15 pp. 167-172.

Books referred

22. Stephen A. Orr "Mining Engineering Handbook" pp 1838-1842
23. Howard L.Hartman, "Introductory Mining Engineering"

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