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ARTICLE

Design and Preparation of the Epoxy Resin Based Sandwich Composite with Broad-Band Wave-Absorbing Properties in C-Band

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Abstract: A sandwich composite with broad-band wave-absorbing properties in C-band was designed and prepared, and the electromagnetic parameters and reflectivity of the composite board were analyzed by a coaxial cable method and a vector network analyzer. The thickness of the composite laminate is 5 mm, and the surface layer of the board and the bottom layer are the glass fiber/epoxy resin composite material, and the Fe50Ni50 powders/butyl rubber nanocomposite is the interlayer. Spherical Fe50Ni50 powders with a particle size of about 100 nm were prepared by a liquid-phase reduction method, and a two-step blending method was used to prepare the Fe50Ni50/butyl rubber nanocomposite. The result shows that the wave-absorbing mechanism of the interlayer is the magnetic loss in the frequency band of 2~18 GHz. The matching of the surface layer and the interlayer is the key to obtain the broad-band wave-absorbing properties, and the good wave-absorbing properties can be obtained by adjusting the thickness of the surface layer and the interlayer. When the thickness of the composite laminate is 5 mm and the thickness of the interlayer is 2 mm, the wave-absorbing frequency band for *R* being less than -10 dB, is in the range of 5.6~7.6 GHz and 16.8~18 GHz, and the width of wave-absorbing band reaches 3.2 GHz, and the wave-absorbing bandwidth in the C-band is 2 GHz, which has achieved a breakthrough.

Key words: nanocomposite materials; wave-absorbing properties; C-band; alloy nano-powders

Radar-absorbing materials (RAM) are used in stealth technologies for concealment of an object from radar detection[1-3]. RAM mainly includes wave-absorbing coatings and structural absorbing composite materials. Wave-absorbing coatings can only be used in the known frequency band because of the thin thickness and a narrow wave-absorbing frequency band. While, wave-absorbing properties of structural RAM can be designed in a composite material which can serve as reinforcement, so that structural RAM can not only resist a force but also has the function of absorbing wave. Therefore, the wave-absorbing properties of the structural RAM can be designable with enough thickness. That is to say, the wave-absorbing properties in low frequency (especially being less than 8 GHz) can be improved by adjusting the thickness of materials. Meanwhile, structural RAM also has advantages of broadband absorption properties and design-ability of the wave-absorbing properties which makes it be the frontier topic in current researches[4,5]. The key points of the structural RAM mainly include designable technologies and mechanisms of broadband absorption, preparation methods and techniques of wave-absorbing composites, and studies of wave-absorbing agents, etc. And the preparation of absorbent and the design of wave-absorbing composite materials are particularly important among them[6,7].

Sandwich composites are one of the main forms of structural RAM[7]. The thickness of sandwich composites for aircrafts is generally less than 5 mm, which requires

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wave absorption in the frequency range of 2~18 GHz. In the current researches of absorbing materials, when the material thickness is less than 5 mm, the wave-absorbing performance of material laminate in X-band (8~12 GHz) is better, but always shows poor absorption performances in C- band (4~8 GHz)[4]. Hence, when the material thickness is less than 5 mm, how to achieve better wave-absorbing performance in the band whose frequency is less than 8 GHz, is a key problem[5].

In this paper, in view of the above problems, a 5 mm thickness composite laminate with sandwich structure was designed, the upper and lower layers of the laminate were made of glass fiber/epoxy composites, and the middle layer was made of a kind of nanocomposite, FeNi alloy powders/IIR. By adjusting the thickness of the upper layer and the middle layer, the broad band absorbing performance could be obtained in the C-band.

There are two main categories in the study of absorbing agents, the one is dielectric loss type, such as graphene, and carbon nanotube[8-12], and the other is magnetic metal powder. The main advantage of dielectric absorbing agent is low density, but the disadvantage is that its dielectric constant is large and it has no magnetic properties, so it has poor matching performance with air impedance. Nano magnetic alloy powders are the focus of current researches in RAM because of their good thermal stability, high permeability and electromagnetic loss, and good penetration of electromagnetic wave etc.[13,14]. Our group has researched different kinds of magnetic metal powder wave-absorbing agents for long time, prepared and studied radar wave absorbing properties of these powders, including polygon nickel powders and sphere Fe50Ni50 powders with particle size of about 100 nm, amorphous/nanocrystalline powders and FeSiAl powders with particle size of 30 μm and so on[15-20]. Furthermore, the problem of dispersion of magnetic alloy powders in the matrix with high powder content has been solved and magnetic alloy powders/epoxy resin (or rubber) composites have been fabricated of which mechanical properties and wave-absorbing properties have been studied in detail[21-23]. In these studies, the most important technology is the preparation of magnetic metal powders/epoxy resin nanocomposites and magnetic metal powders/rubber nanocomposites. It is easy to be agglomerated for magnetic alloy nanopowders because of their magnetic properties and large specific surface area and high surface energy. So the aim that the magnetic nanopowders are dispersed in nano-scale in resin matrix, especially in the solid rubber matrix is very difficult to be achieved. Therefore, the preparation process of composites should be closely integrated with that of magnetic nanopowders.

On the basis of the previous researches, butyl rubber (IIR) with good resistance to environmental performance, high strength and strong adhesive properties was adopted as the matrix, instead of silicone rubber (SIR) with poor self viscosity and low intensity. At the same time, Fe50Ni50 alloy nanopowders, which has high permeability, was used as absorber, instead of pure Ni powders and FeCuNbSiB nanocrystalline powders. And Fe50Ni50 nanopowders/IIR nanocomposite with good flexibility and resistance to environmental properties was fabricated, of which powder mass fraction was 80%. Then the nanocomposites were used as the interlayer to prepare the "glass fiber/epoxy resin" composite laminate, and it vulcanized along with the epoxy resin, which could ensure high bonding strength of the interlayer and other epoxy resin layers. This paper explored the wave-absorbing properties of Fe50Ni50 nanopowders and Fe50Ni50 powders/IIR nanocomposites in 2~18 GHz band, and optimized the thicknesses of nanocomposites and layers of the composite laminate in order to realize the precise design of the wave-absorbing properties of the composite laminate and the effective broadening of the absorption band.

1 Experiment

1.1 Preparation and characterization of Fe50Ni50 powders

The compound of $NiSO_4$ (AR grade) and $FeSO_4$ (AR grade) with the Fe/Ni molar ratio of 1/1 to 1/0.1 in the water solution, reacted with N_2H_4 for about 30 min to generate FeNi powders. The reaction conditions were pH value of about 14 and the temperature of 85 °C. The powders were separated from water solution by magnetic separation method. And the reaction equations are as follows:

$$2FeSO_4 + N_2H_4 + 4NaOH \rightarrow 2Fe\downarrow + N_2\uparrow + 4H_2O + 2Na_2SO_4 \quad (1)$$

$$2NiSO_4 + N_2H_4 + 4NaOH \rightarrow 2Ni\downarrow + N_2\uparrow + 4H_2O + 2Na_2SO_4 \quad (2)$$

Experiments show that FeNi alloy nanopowders prepared by liquid phase reduction method will be rapidly oxidized in 1 h and cannot be stored for long time when the content of Ni in FeNi alloy nanopowders is lower than 33 at%. Therefore, the content of Ni was modified to 50 at% in this study. Here, the obtained powders were named Fe50Ni50 powders（the composition is the atom rate）.

The phase identification of the FeNi powders was performed by X-ray diffraction (XRD) on a Bruker-axe D8 ADVANCE X-ray diffractometer with Cu Kα radiation. The test conditions were that tube voltage was 40 kV, the current was 40 mA, and the step was 0.02°. There are $FeNi_3$ phase and Fe_2O_3 phase, for that a small amount of Fe powders were generated and oxidized in the reaction process (Fig.1).

Particle microstructures and morphologies were observed by JEM-2100 high resolution transmission electronic microscopy (HR-TEM). The Fe50Ni50 powder is a single regular spherical particle, and the size of particle is 20~100 nm. The Fe50Ni50 alloy powder is composed of two layers with different components. The content of Ni of the core layer is lower than that of the outer layer, while the content of Fe is opposite. There is s clear interface between the two layers (Fig.2).

1.2 Preparation and characterization of Fe50Ni50 powders/IIR nanocomposites

Butyl rubber (IIR) was dissolved in toluene solvent, and then appropriate amount of sulfur, accelerator DM, ZnO, and stearic acid, etc. were added into the mixture, stirred to mix and dissolved evenly. At last, the extracted Fe50Ni50 powders were mixed with the mixture and the toluene was removed. The remaining was fully mixed with two roll mill to obtain Fe50Ni50 powders/IIR nanocomposite, and the powder content was 80 wt%. Fig.3 shows the preparation flow chart of Fe50Ni50 powders/IIR nanocomposite.

The nanocomposite was pressed into the thin film by the powder pressing machine, and it was cured at temperature of 160 °C for 1 h, and the pressure of 1 MPa.

The microtopographies of the films were observed by a field emission scanning electron microscopy (JSM-6701F), and the ingredient was measured by SEM-EDS.

The Fe50Ni50 nanopowders are easily reunited and cannot be exposed to the air for the large specific surface area and

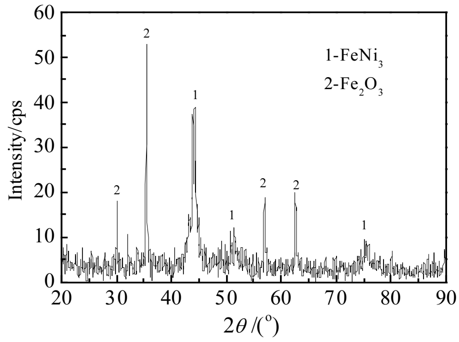


Fig.1 XRD pattern of FeNi powders

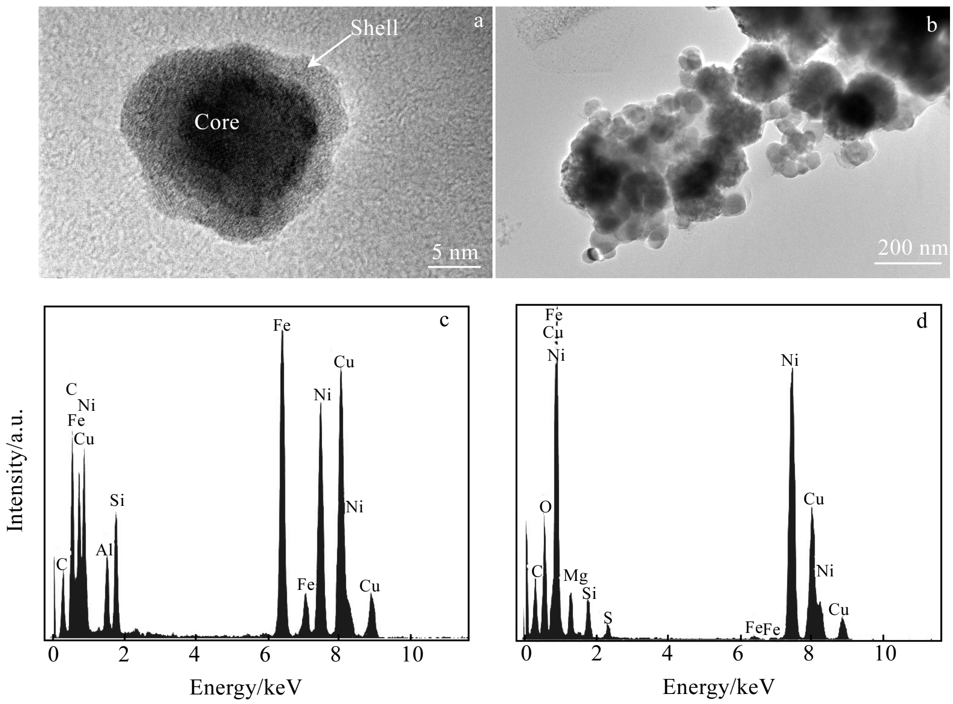


Fig.2 TEM images (a, b) and EDS spectra (c, d) of FeNi powders: (a) the particle structure, (b) the powders, (c) element composition in core layer, and (d) element composition in shell layer

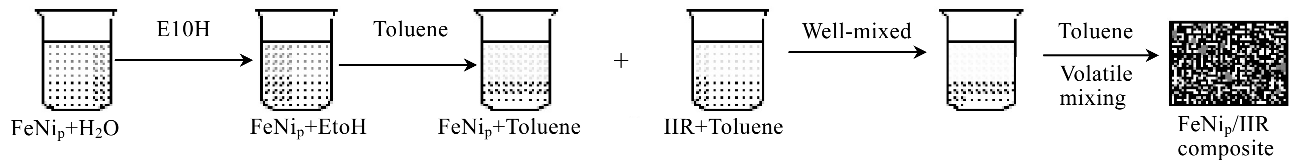


Fig.3 Flow chart of Fe50Ni50 powders/IIR nanocomposites preparation

high surface energy. What is more, the aim that the FeNi powders were dispersed in nano-scale in IIR matrix is very difficult to be achieved for high weight percentage and IIR as a kind of high elastic solid[4,5].

SEM images show that the FeNi powders evenly distribute in the IIR matrix, and nano-scale dispersion effect is achieved (Fig.4). The bright parts in Fig.5 are proved to be Fe50Ni50 powders by EDS, and the dark parts in Fig.5 represent IIR (the Ni content in particle is about 35 wt%, and the Fe content is 25 wt%). SEM analysis shows that the method of powders scattered in IIR matrix and the technology of nanocomposites preparation is feasible.

The density of the Fe50Ni50 powders/IIR nanocomposite is 1.9 g/cm^3, and the resistivity of the nanocomposite is 10^7, while that of PE is 10^{11}.

1.3 Preparation of fiberglass/interlayer/epoxy resin composites

The layers of twill fiberglass/E-51 epoxy resin (specification of the fiberglass: sw210-90b, made by Nanjing Fiberglass Research and Design Institute Co. Ltd.) were laid in upper surface and lower surface of the flat mould, and the Fe50Ni50 powders/IIR nanocomposite as the interlayer was laid in the middle of the flat mould, which formed a sandwich structure, fiberglass/interlayer/fiberglass composite laminate. The laminate was cured at the temperature of 160 °C for 60 min and the area pressure of 1 MPa.

The microstructure of the composite laminate was observed by a body microscope. Fig.6 shows the sketch of laminate and the microstructure of the composite laminate. The interlayer thickness is 1 mm. No defects are found in the combination of the interlayer and fiberglass/E-51 layer.

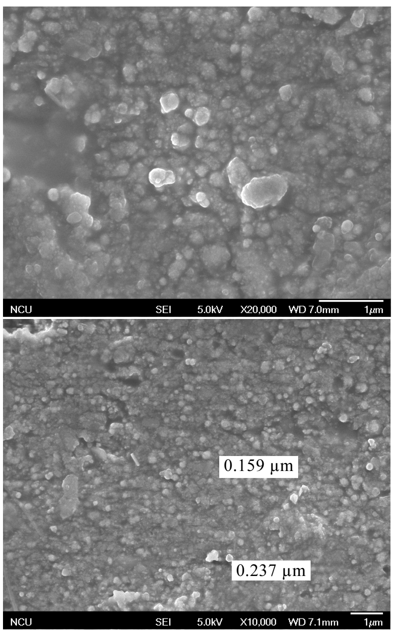
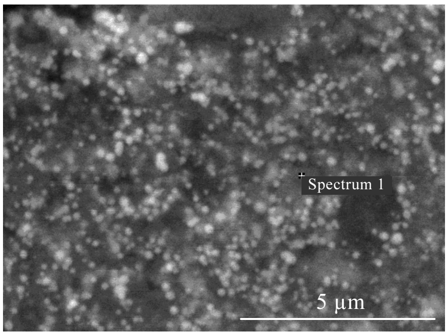


Fig.4 Microstructures of FeNi powders/IIR nanocomposites



Element	Content/wt%
C	1
O	35
Na	3
S	3
Fe	27
Ni	31

Fig.5 SEM image and EDS analysis of FeNi powders/IIR nanocomposites

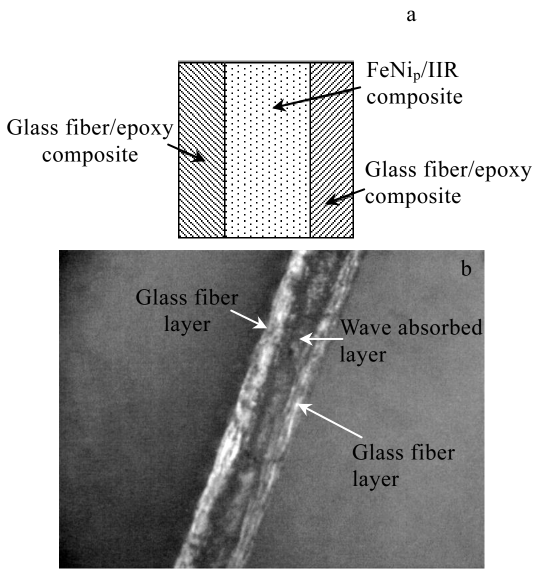


Fig.6 Laminate sketch (a) and microstructure (b) of the composite laminate

2 Results and Discussion

2.1 Absorption properties of Fe50Ni50 nanopowders

The electromagnetic parameters, the complex permittivity and permeability, of the samples were tested by Agilent E8363 vector network analyzer in a frequency range of 2~18 GHz.

The sample made up of 80wt% Fe50Ni50 powders and 20wt% paraffin, was pressed into a coaxial ring with the inner diameter of 3 mm and outer diameter of 7 mm.

The electromagnetic parameters of Fe50Ni50 nanopowders are shown in Fig.7. In the frequency range of 2~18

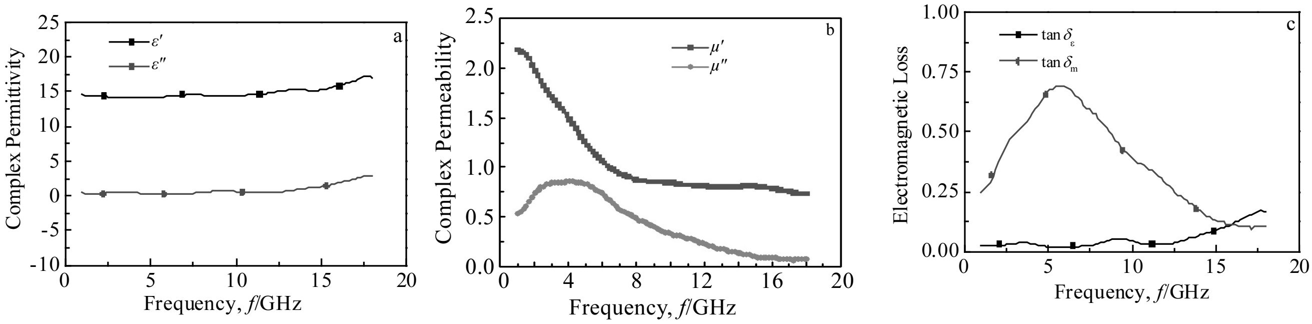


Fig.7 Electromagnetic parameters of Fe50Ni50 nanopowders: (a) ε', ε'', (b) μ', μ'' and (c) tanδ_ε, tanδ_m

GHz, the real part of the complex permittivity, ε', of Fe50Ni50 nanopowders is about 15 (Fig.7a). And the imaginary part of the complex permittivity, ε'', increases with the frequency increasing (Fig.7a), because the coupling effect between particles is enhanced and the conductive network is formed due to the action of electromagnetic wave. The electrical conductivity increases, which will lead to ε'' increased along with the increasing of frequency (Eq.3):

$$\varepsilon'' = \sigma/(2\pi f \varepsilon_0) \quad (3)$$

In Eq.(3), ε_0 is permittivity of vacuum, f is the frequency of electromagnetic wave, and σ is electrical conductivity.

The real part of complex permeability of Fe50Ni50 nanopowders, μ' is about 2~1 in the frequency range of 1~6 GHz. In addition, μ' decreases with the increase of frequency (Fig.7b).

The loss mechanism of Fe50Ni50 nanopowders was magnetic loss, because the tan value of ε, tanδ_e is less than tanδ_m in frequency range of 2~16 GHz. As shown in Fig.7c, the tan value of μ, tanδ_m of the Fe50Ni50 nano powders is 0.5~0.7 in the frequency range of 2.5~9 GHz, which means that theFe50Ni50 nanopowders displays good wave-absorbing property.

In addition, the wave absorption characteristics of Fe50Ni50 nanopowders are very similar to those of pure Ni nanopowders (diameter 100 nm), while absorption properties of the former are significantly better than those of the latter[24,25]. In the frequency range of 2~18 GHz, the ε' of Fe50Ni50 nanopowders and Ni nano powders are both large, about 15; meanwhile, the ε'' increases with frequency increasing. But tanδ_m of Fe50Ni50 nanopowders is obviously larger than that of Ni nanopowders, and the frequency bandwidth of Fe50Ni50 nanopowders is 3~9 GHz when tanδ_m is more than 0.5, which is lower than that of Ni nanopowders (6~12 GHz). Hence, it is beneficial to improve the wave absorbing performance in the frequency band especially being less than 6 GHz by the FeNi nanopowders instead of the pure Ni powders.

2.2 Absorption properties of Fe50Ni50 powders/IIR nanocomposites

The electromagnetic parameters of the Fe50Ni50 powders/IIR nanocomposites were measured by Agilent E8363 vector network analyzer in a frequency range of 2~18 GHz.

The absorption mechanism of RAM includes two aspects. On the one hand is that the electromagnetic wave is attenuated by dielectric loss or magnetic loss of the RAM when the electromagnetic wave enters inside the material. On the other hand is that the electromagnetic wave is attenuated by the interference effect of reflection wave formed on the surface of the material.

Consequently, the wave-absorbing materials need to meet two requirements[26]. Firstly, when electromagnetic wave is normal incidence, the electromagnetic wave must enter the interior of the material as much as possible. That is to say, the electromagnetic matching between the air and the sample's surface must be suitable and the electromagnetic parameters of the material should meet $\mu_r/\varepsilon_r=1$ as far as possible. Relative permeability (μ_r) of nonmagnetic materials is very small (about 1) in the high frequency band. On the contrary, relative permittivity (ε_r) is large. For example, ε_r of epoxy resin matrix material is more than 4 when the frequency, f, is more than 1 GHz. In order to meet good electromagnetic matching, the μ_r needs to be increased and ε_r needs to be decreased.

Compared with that of Fe50Ni50 powders, the ε_r of the Fe50Ni50 powders/IIR nanocomposites is significantly decreased and the value is about 10 in 2~18 GHz (Fig.8a). At the same time, the μ_r of the nanocomposites is 2~1 in 1~6 GHz, and is about 1 in 6~18 GHz (Fig.8b). It is beneficial to reduce the reflectivity of the radar wave in the surface of the nanocomposite, and more electromagnetic wave can enter into the nanocomposite.

When the electromagnetic wave enters the interior of the sample, the electromagnetic wave can quickly be attenuated, namely electromagnetic loss of the specimen should be large, and the material loss tangent value, tanδ, needs to be

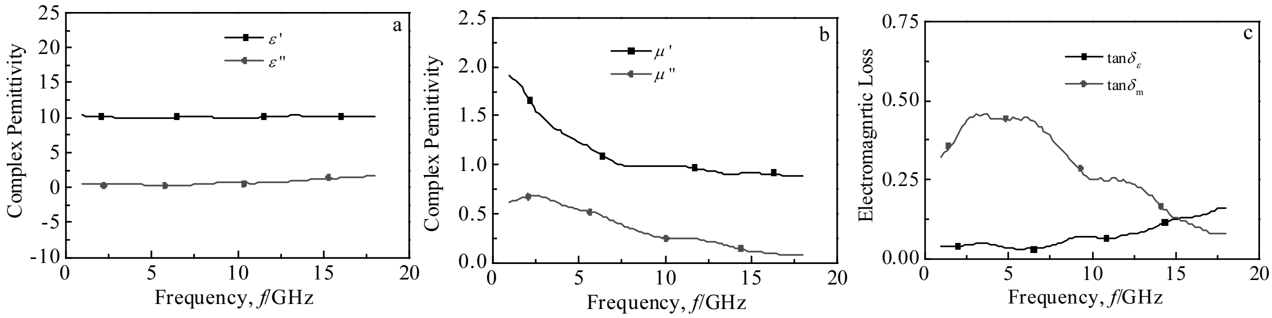


Fig.8 Electromagnetic parameters of Fe50Ni50 powders/IIR nanocomposites: (a) ε', ε'', (b) μ', μ'' and (c) $\tan\delta_\varepsilon$, $\tan\delta_m$

large, generally larger than 0.3. Only in this way, the material can have excellent wave-absorbing properties. The loss mechanism of Fe50Ni50 powders/IIR nanocomposite is electromagnetic loss (Fig.8c). The $\tan\delta_m$ of the nanocomposites is more than 0.3 in 1~9 GHz and about 0.45 in 3~7 GHz. Hence, the nanocomposite material has good absorption performances in 1~9 GHz. But compared with those of Fe50Ni50 powders, the wave-absorbing properties of the nanocomposites are decreased significantly because IIR is a kind of diamagnetic material, which can decrease the magnetic properties of the nanocomposites.

According to the absorption mechanism of RAM, the overall performances of the RAM (i.e. the reflectivity *R*) are jointly determined by the electromagnetic wave absorbing effect of the material (the magnetic loss and dielectric loss) and the interference effect of reflected wave formed on the surface of the material. Therefore, wave absorbing properties of monolayer material are determined by the μ, ε, μ/ε, $\tan\delta_m$ and thickness of the material *d*. These parameters such as μ, ε and $\tan\delta_m$ are related to the frequency of electromagnetic wave. When the frequency is fixed, the value of μ_r/ε_r determines the surface reflectivity of the material, which is the maximum wave-absorbing (upper limit) caused by the dielectric loss or magnetic loss. The $\tan\delta$ and *d* determine the basic amount of wave-absorbing in the specific frequency. The wave absorbing amount is much greater when the both values are larger. The wavelength λ of the electromagnetic wave which can enter the material is decided by the μ_r and ε_r of the material. The interference effect works when *d* is equal to $(1/4)k\lambda$. Meanwhile, the absorption peak appears, and the wave-absorbing amount is the most.

According to the transmission line theory, the reflectivity *R* can be represented as follows when the electromagnetic wave is normal incidence.

$$R = 20\lg\left(\frac{Z-1}{Z+1}\right) \tag{4}$$

$$Z = \sqrt{\mu_r/\varepsilon_r}\tanh\left(\frac{j2\pi f\sqrt{\mu_r\varepsilon_r}d}{c}\right) \tag{5}$$

Where, *Z* is normalized input impedance. *C* is the speed of light, *f* is frequency, μ_r and ε_r is the complex permeability and complex permittivity of samples, respectively, *d* is the thickness of samples and tanh is the hyperbolic tangent function.

Fig.9 shows the reflectivity, *R,* of Fe50Ni50 powders/IIR nanocomposites with different thicknesses. As the thickness of the nanocomposite reaches 1.5 mm, the electromagnetic wave absorption peak (i.e. main absorption peak) begins to appear and shifts toward the direction of the lower frequency along with the increase of the thickness. As the thickness is up to 5mm, the secondary absorption peak of the nanocomposite begins to appear.

Absorbing characteristics of different wave absorbing requirements could be designed by changing thicknesses of composites as shown in Table 1. When the thickness of Fe50Ni50 powders/IIR nanocomposite is 2 mm, the absorption band width reaches 3 GHz when *R* is less than -10 dB in 2~18 GHz, which shows the nanocomposite has excellent wave-absorbing properties.

2.3 Optimization of absorption properties of composite laminates

According to the absorption mechanism, a little electromagnetic wave can be generally attenuated by the way of the magnetic loss, and a large number of electromagnetic waves are attenuated by interferential absorption in narrow frequency band. Therefore, the performance of electromagnetic wave-absorption depends on the external surface

Table 1 Thicknesses and absorbing bands of Fe50Ni50 powders/IIR nanocomposites

d/mm	Absorption frequency band /GHz (*R*⩽-10 dB)	Absorption band width/GHz (*R*⩽-10 dB)	Center frequency of the main absorption peak/GHz
1.5	15.28~18	2.7	17.49
2	10.52~13.58	3	11.88
3	5.76~8.82	3.1	7.46
4	4.06~6.10	2	4.91
5	3.04~4.57	1.5	3.72

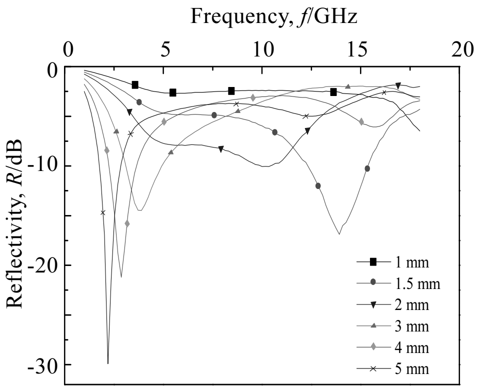


Fig.9 Overall absorption properties of Fe50Ni50 powders/IIR nanocomposites with different thicknesses

reflectivity, the tanδ value and the thickness d of the material. In order to broaden the wave-absorbing band, an effective method is to make full use of the interferential absorption principle. And the single material is divided into a plurality of layers with different electromagnetic parameters, and then a composite laminate is composed of multiple layers. The emphasis of the wave-absorbing properties of the multilayer materials is the thickness and electromagnetic parameters of each layer and the calculation workload of the properties is enormous.

In this paper, a simple multilayer composite laminate was designed and prepared (Fig.6). The interlayer of the composite laminate was Fe50Ni50 powders/IIR nanocomposite as the wave-absorbing layer, and the glass fiber/epoxy resin layer was on the both sides of the interlayer. When keeping the consistent thickness of the composite laminate, wave-absorbing properties in different frequency bands and the wave-absorbing bandwidth could be designed by changes of the thickness of surface layer and the interlayer.

According to the transmission line theory, the wave-absorbing performance of the multilayer material can be calculated. The radar wave is partly reflected and absorbed by interface with input impedance $Z_{in}(K)$ from the free space $Z_0=(\mu_0/\varepsilon_0)^{1/2}$. The electromagnetic reflection coefficient of the absorber is determined by the following formula:

$$\Gamma = \frac{Z_{in}(N) - Z_0}{Z_{in}(N) + Z_0} \tag{6}$$

Reflectivity R is:

$$R = 20\lg\left|\Gamma\right| = 20\lg\left|\frac{Z_{in}(N) - Z_0}{Z_{in}(N) + Z_0}\right| \tag{7}$$

For multilayer composite laminate, only the interlayer, Fe50Ni50 powders /IIR composite, can absorb electromagnetic waves. The surface layer can effectively reduce reflections of external surface of the interlayer, and reflect multiply electromagnetic waves with adding two reflecting surfaces. Fig.10 and Table 2 show that the wave-absorbing performances can be changed by adjusting the thickness of surface layers. When the thicknesses of the interlayer are more than 2 mm, the composite laminate of 5 mm has broadband wave-absorption. When the thickness of the interlayer is certain, the width of absorption frequency band can be broadened by increasing the thickness of the surface layers. Take the 5 mm thickness laminate as an example, compared with the Fe50Ni50 powders /IIR composite, when the thickness of surface layer, interlayer and bottom layer are 0.1, 2 and 2.9 mm, respectively, the wave-absorbing curves of the composite laminate in 2~18 GHz (Fig.10) is similar to that of Fe50Ni50 powders/IIR nanocomposite of 5 mm thickness (Fig.9). The absorption peaks of the 5 mm thickness laminate appear in the frequency band of 5.6~7.6 GHz and 16.8~18 GHz, and the width of absorption frequency band for R less than -10 dB reaches 3.2 GHz, which is twice than that of Fe50Ni50 powders/IIR composite. The center frequency of the absorbing peak is 6.6 GHz, and the corresponding R is -25 dB. The main absorption frequency band for R less than -10 dB extends into C-band.

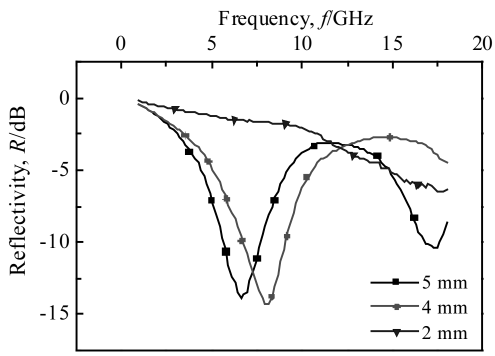


Fig.10 Wave-absorbing properties of the composite laminates

Table 2 Absorption properties of the composite laminate

Composites' thickness, d/mm	Thickness of layers/mm	Absorption frequency band/ GHz ($R\leqslant$-4 dB)	Absorption frequency band/GHz ($R\leqslant$-10 dB)	Center frequency of main absorption peak/GHz
5	GF/interlayer/GF=0.1/2/2.9	(1) 4.06~9.67 (2) 13.92~18	5.59~7.63, 16.81~18	6.61 (-13.84 dB)
4	GF/interlayer/GF=0.1/2/1.9	(1) 4.57~11.37 (2) 17.49~18	6.78~8.99	7.97 (-14.27 dB)
2	GF/interlayer/GF=0.1/1/0.9	12.9~18	-	18 (-6.5 dB)

3 Conclusions

1) The spherical Fe50Ni50 nanoparticles with a uniform diameter of about 100 nm have been prepared by liquid phase reduction method. Fe50Ni50 nanopowders are evenly distributed in butyl rubber material as nano-scale by solvent extraction and solution blending method. The Fe50Ni50 powders/butyl rubber nanocomposite, in which powders are well-distributed, and powder mass fraction is 80 wt%, is successfully prepared. Magnetic loss of nanocomposite is dominant in the range of 2~18 GHz.

2) A simple sandwich composite laminate is designed and prepared. The interlayer of the composite laminate is Fe50Ni50 powders/IIR nanocomposite, and the glass fiber /epoxy resin layer is on the both sides of the interlayer. When keeping the consistent thickness of the composite laminate, wave-absorbing properties can be designed by changes of the thickness of surface layer and the interlayer. When the thickness of the interlayer is more than 2 mm, the 5 mm thickness laminate has broadband wave-absorption. The main absorption frequency band for *R* less than -10 dB is in the range of 5.6~7.6 GHz to extend into C-Band. The width of absorption frequency band for R less than -10 dB reaches 3.2 GHz in 2~18 GHz, which presents excellent broad-band wave-absorbing properties.

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在C波段具有宽频吸波性能的环氧树脂基夹层复合材料设计与制备

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摘 要：设计和制备了一种在C波段上具有宽频吸波性能的夹层复合材料，并用同轴电缆法和矢量网络分析仪分析了复合材料板的电磁参数和反射率。复合材料板厚度为 5 mm，板表层与底层为玻璃纤维/环氧树脂复合材料，以Fe50Ni50粉体/丁基橡胶纳米复合材料为中间夹层。采用液相还原法制备了粒径约为100 nm的球形Fe50Ni50粉末，采用二步共混法制备了Fe50Ni50/IIR复合材料。结果表明, Fe50Ni50粉体/IIR纳米复合材料在 2~18 GHz频带上以磁损耗为主。表层与夹层的匹配是获得宽频吸波特性的关键，可以通过调整表层与夹层的厚度获得良好的吸波性能。当复合材料板厚度为 5 mm、夹层厚度为 2 mm时，板的*R*≤-10 dB的吸波频带为5.6~7.6 GHz和16.8~18 GHz，吸波带宽达到3.2 GHz，该材料在C波段吸波带宽达到2 GHz，取得了突破。

关键词：纳米复合材料; 吸波性能; C波段; 合金纳米粉

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