Electromagnetic Shielding Performance of CF/EP Composites with Sandwiched Structure

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Abstract. Carbon fiber reinforced polymer matrix composites are widely used in many fields due to their excellent mechanical properties. Moreover, the carbon fiber composites can also be used as electromagnetic shielding materials because carbon fibers have good electrical conductivity. However, the formation of effective conductive network in the unidirectional composites is restricted because each carbon fiber is surrounded by the resin and separated from each other. As a result, the electromagnetic shielding performance of the unidirectional carbon fiber composite is not satisfied. In this paper, the single walled carbon nanotube (SWCNT)/PEK-C films with good electrical conductivity were prepared by using the coating method. The conductive films were then placed between layers of unidirectional carbon fiber prepreg to obtain the composites with sandwich structure by the compression molding technology. The results showed that the electromagnetic shielding effectiveness of the composites sandwiched with the films was significantly improved compared with the neat unidirectional composite. The absorption-dominated shielding mechanism of the composites was also proved. Meanwhile, the composites also exhibited good mechanical properties.

Keywords: Carbon fiber composites, conductive film, electromagnetic shielding performance, carbon nanotube, PEK-C

1. Introduction

Digital electronic information technology has grown rapidly, greatly improving life for individuals. The electromagnetic environment is becoming ever more complex, as a result of the increasing importance of the electromagnetic compatibility (EMC) and electromagnetic interference (EMI) problems caused by electromagnetic waves. To protect either the correct application of technology and human health, it is essential that efficient electromagnetic shielding materials be developed [1-2].

Traditional shielding materials are mostly some metals and their alloys with strong electrical conductivity. However, these materials are limited in use due to their high density, low flexibility, and quick corrosion [3]. In addition, the primary foundation in the shielding mechanism of metallic materials is reflection, which is subject to secondary pollution [4].

Therefore, the development of efficient, lightweight, and sustainable electromagnetic shielding materials has grown as a new demand in the improvement of electronic equipment protection. Due to their low weight, high processability, structural designability and corrosion resistance, the conductive polymer composites (CPCs) have attracted a lot of curiosity and have proven to be a significant research trend in the field of electromagnetic shielding materials [5].

Because carbon fibers themselves have excellent electrical conductivity, carbon fiber reinforced polymer matrix composites (CFRP) can also be used as electromagnetic shielding materials. [6]. Munalli et al. [7] concluded that the carbon cloth reinforced epoxy composites have excellent electromagnetic shielding effectiveness (EMI SE). However, in unidirectional CFRP, the carbon fibers are arranged in parallel with each other and are tightly wrapped and separated apart by the resin matrix. Thus, the formation of a complete and effective conductive network structure was prevented, which has a negative effect on the electromagnetic shielding performance of the composites [8].

The previous studies showed that adding carbon nanofillers as graphene or carbon nanotubes (CNT) to composite composites can significantly improve the materials' electromagnetic shielding properties [9]. Jiang et al. [10] prepared CNT films with excellent electrical conductivity by placing them between the composite layers to form a sandwich structure. During the shielding process, the electromagnetic waves were reflected several times inside the material, which led to the enhancement of the electromagnetic shielding performance of the composite. However, due to the lack of polar functional groups on the surface of the conductive carbon nanofillers, the lack of chemical bonding between the films and the resin can adversely affect the interlayer adhesion of the composites.

In this paper, single-walled carbon nanotubes (SWCNT) were homogeneously dispersed in PEK-C resin solution, and the SWCNT/PEK-C conductive films were prepared by coating method and placed between unidirectional carbon fiber prepreg layers. The results showed that the composite has good electromagnetic shielding properties and also exhibits good mechanical properties due to the good bonding between PEK-C and epoxy resin.

2. Materials and methods

2.1. Materials

PEK-C powder was supplied by Xuzhou Engineering Plastics Factory; SWCNT dispersion was made in the laboratory; Unidirectional carbon fiber/epoxy prepreg (USN05400) was obtained from Weihai Guangwei Composites Company, China. N-methyl pyrrolidone (NMP) was supplied by Tianjin Damao Chemical Reagent Factory, China. Polyvinyl Pyrrolidone (PVP) was purchased from Wuxi Yatai United Chemical Co.

2.2. Preparation of conductive film and composites

0.15g of SWCNT and 0.075g of PVP powder were added to 100ml of NMP solvent and 100ml of DMAc solvent respectively. After mechanical stirring, homogenization and ultrasonic dispersion, the SWCNT dispersion was obtained. 12g of PEK-C resin was then added to the dispersion and the two SWCNT/PEK-C solutions were obtained. The prepared solution was evenly applied to the glass plate with a coating rod and dried to obtain the film with a thickness of 14μm. Afterwards, the coating and drying process were repeated twice to obtain the film with a thickness of 44um.

The composites were prepared by placing different sheets of SWCNT/PEK-C conductive films in a certain sequence between layers of unidirectional CF/EP prepreg using a compression moulding. For the convenience of discussion, the composites are named xF/P(y), where F and P represent the conductive film and prepreg respectively, x represents the number of sheets of film and y represents the number of layers of prepreg between the two layers of film. The composite with only one film is named 1F/P. The thickness of the composite is 2mm and the total number of layers of prepreg used is 36.

2.3. Characterisations

The cross-sectional morphology of the films was examined using an IGMA scanning electron microscope (Carl Zeiss, Germany).The electrical conductivity of the SWCNT/PEK-C films was measured using an RTS-8 resistivity meter (Four Probe Technology, China) with a current range of 1mA. The interlaminar shear strength (ILSS) and flexural strength of the composites were tested on a DDL50 universal testing machine according to ASTM D2344. The scattering and electromagnetic parameters of the samples were measured in the X-band (8.2-1 2.4GHz) frequency range using a N5230C PNA-L vector network analyzer (Agilent Technologies, USA) with a sample size of 22.86mm x 10.16mm x 2mm. The total shielding effectiveness, reflection shielding effectiveness, and absorption shielding effectiveness of the composite were calculated according to the following equations [11]:

$$SE_T = SE_R + SE_A + SE_M \tag{1}$$

$$SE_T = 10\log\frac{1}{|S_{12}|^2} = 10\log\frac{1}{|S_{21}|^2} \tag{2}$$

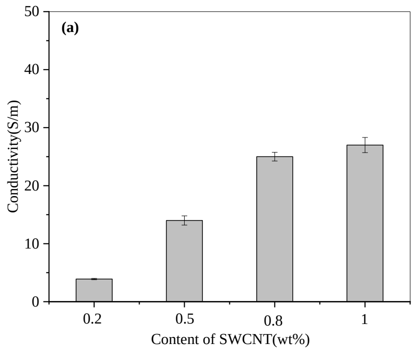
$$SE_A = 10\log_{10}\left(\frac{1-|S_{11}|^2}{|S_{12}|^2}\right) \tag{3}$$

$$SE_R = 10\log_{10}\left(\frac{1}{1-|S_{11}|^2}\right) \tag{4}$$

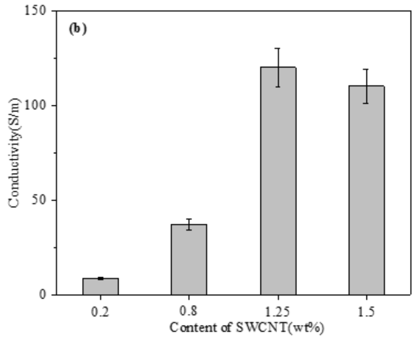
3. Results and discussion

3.1. Conductivity of SWCNT/PEK-C films

Fig.1. shows the conductivity of the SWCNT/PEK-C films prepared using the two solvents with a thickness of 14μm. It is clearly shown that the conductivity of the films prepared using NMP solvent was significantly greater than that of the films prepared using DMAc solvent. Obviously, the use of various solvents gave the different impact on the dispersion of SWCNT. Both of NMP and DMAc are polar solvents, however, NMP has a greater level of polarity than DMAc. Thus, it is relatively easy to separate SWCNT from their bundles in the NMP solvent. In the drying process, the distance between the carbon nanotubes decreased owing to the solvent's volatilization. The separated carbon nanotubes were reagglomerated together under the impact of van der Waals and Coulombic gravitational connections.



(a)Using DMAc



(b)Using NMP

Figure 1. Electrical conductivity of the prepared SWCNT/PEK-C films using different solvents Example of a figure caption

Fig. 2 shows the conductivity of SWCNT/PEK-C films prepared using NMP solvent with a thickness of 44μm. When the SWCNT content was 0.2wt%, 0.8wt%, 1.25wt% and 1.5wt%, respectively, the conductivity of the films was 10S/m, 83S/m, 160S/m and 150S/m. In comparison to the film with a thickness of 13μm, the 44μm film has much higher conductivity. This is that the conductive network of the 44-μm film has a substantially more complete lap, allowing it to decrease the restriction of electrons by carbon tubes and improve the efficiency of the transport of electrons.

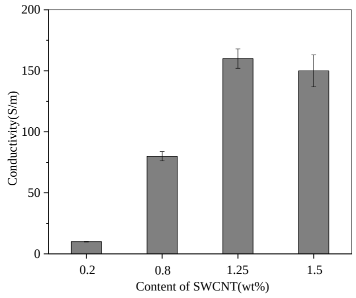


Figure 2. Electrical conductivity of SWCNT/PEK-C films

Fig.3. shows the cross-sectional images of the SWCNT/PEK-C film with a thickness of 44μm. The carbon nanotubes in the film are interspersed between multiple conductive networks, thus establishing the conductive networks in the resin in series and making the conductive channels more continuous and complete, increasing the conductivity of the film.

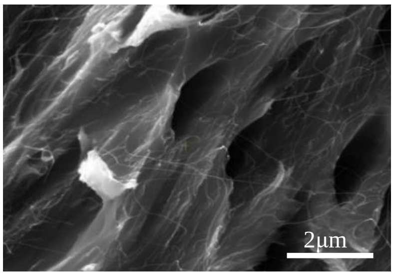


Figure 3. Electrical conductivity of SWCNT/PEK-C films

3.2. Electromagnetic shielding of composite materials

Fig.4. shows the EMI SE of composites containing different number of film sheets. The EMI SE of the CF/EP composite without film was 12.45dB. The EMI SE of the 1F/P, 4F/P(6), 5F/P(6) and 6F/P(6) at X-band was 14.69dB, 22.69dB, 23.28dB and 25.34dB, respectively. When one film was added to the composite, the shielding performance was only 14.69dB. Apparently, the EMI shielding efficiency composites was not a simple combination of that of the film and the neat composite.

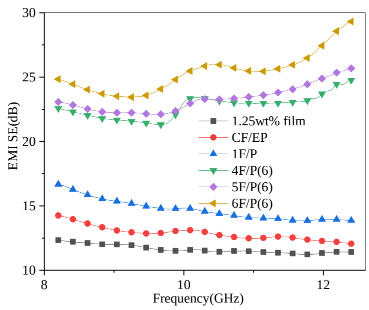


Figure 4. EMI SE values of films and composites

The EMI SE of the composites shows an increasing trend with the increase of number of the films, which is due to the fact that the SWCNT/PEK-C film has a complete conductive network structure.

Fig.5. shows the SE_R and SE_A of the composites in the X-band. The SE_R and SE_A of neat CF/EP composites were 3.12dB and 8.94dB, respectively. The SE_A of 4F/P(6), 5F/P(6), and 6F/P(6) was 17.42dB, 17.80dB, and 20.18dB respectively, and their SE_R was 5.27dB, 5.48dB, and 5.16dB, respectively. It can be seen that the SE_A of the composites increased with the increasement of the number of films, while the SE_R remained the same. When the number of films increased, the interface between the reflection and scattering of electromagnetic waves in the composite increased. Thus, it is difficult for the electromagnetic waves to escape from the composite, which is reflected by the increased absorption loss in the composite. As shown in the literature, the reflection loss hardly varies

with the number of the sandwiched films [12], while the absorption loss increases with the number of the sandwiched films.

The increase in shielding effectiveness of the composites was mainly caused by the increase in absorption loss. The SE_A values of all the composites accounted for more than 75% of the SE_T values, indicating that the electromagnetic shielding mechanism of the composites was mainly based on the absorption mechanism.

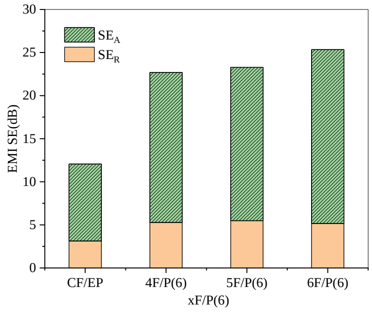
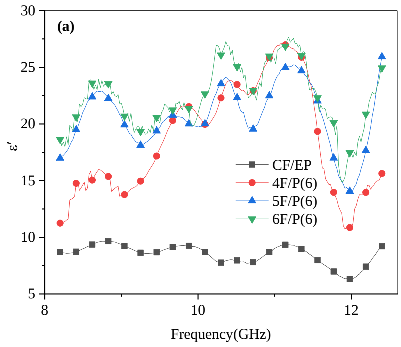


Figure 5. SER and SEA for composites

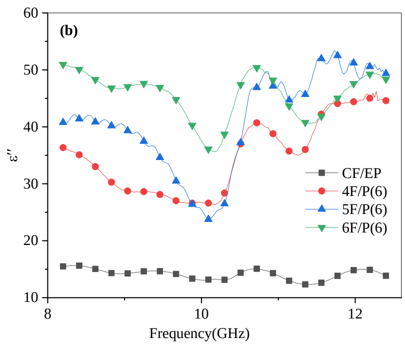
The increase in shielding effectiveness of the composites was mainly caused by the increase in absorption loss. The SE_A values of all the composites accounted for more than 75% of the SE_T values, indicating that the electromagnetic shielding mechanism of the composites was mainly based on the absorption mechanism.

In order to further investigate the electromagnetic wave absorption properties of the composites, the dielectric properties of the composites were studied. Since the carbon fibers and the films in the composite were not magnetic, only the complex permittivity of the composite was discussed and analyzed.

The complex permittivity of the composites is shown in Fig.6. It is known that the real part (ε') and the imaginary part (ε'') of the complex permittivity increased gradually with the increase of the number of films. Moreover, the ε' and ε'' of the composites fluctuated greatly with the increase of frequency, which is due to the fact that the dipole moment of the carbon material in the composites was more difficult to reorient with the direction of the applied electric field at high frequencies [13].



(a) real part (ε')



(b) imaginary part (ε'')

Figure 6. Complex permittivity of composites

Fig.7. shows the variation curve of $\tan\delta_\varepsilon$ for the composites. It is known that the $\tan\delta_\varepsilon$ values for all composites were greater than 1, which indicated that the composites had a strong loss absorption effect. Similarly, with the increase of the number of films, the $\tan\delta_\varepsilon$ values gradually decreased. This result indicates that the added films played an important role in the electromagnetic wave loss of the composites.

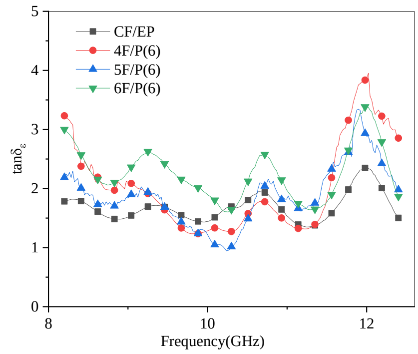


Figure 7. Variation curves of $\tan\delta_\varepsilon$ of the composites

3.3. Mechanical Properties of composites

The ILSS and the flexural strength of CF/EP composites are shown in Fig.8. The ILSS for the neat CF/EP composite was 65.74MPa and the flexural strength was 1257MPa. The ILSS of the 4F/P(6), 5F/P(6) and 6F/P(6) were 59.52MPa, 62.10MPa and 60.26MPa, respectively, and their flexural strengths were 1308MPa, 1265MPa and 1213MPa, respectively. The results proved that the mechanical properties of the CF/EP composites with the SWCNT/PEK-C films were also the same as that of the neat CF/EP composite. It may be concluded that the addition of SWCNT/PEK-C films had no negative effects on the mechanical properties of the composites due to the good bonding between the film and the epoxy resin [14].

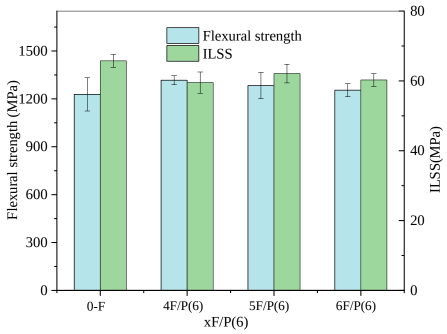


Figure 8. Mechanical properties of composites

4. Conclusion

(1) When the SWCNT content was 1.25wt% and the thickness was 44m, the film conductivity was 160S/m. The films prepared with NMP solvent have significantly higher conductivity than the films made using DMAc solvent.

(2) With the increasement of number of added films, the electromagnetic shielding performance of the composites increased. The EMI SE of the composite was 25.34dB when the number of added film was 6. The composite exhibited an absorption-based shielding mechanism.

(3) The composites also has good mechanical properties due to the good bonding between the film and resin layers.

Acknowledgments

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