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Microwave absorbing properties of activated carbon-fiber felt dipole array/epoxy resin composites

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Abstract Microwave absorbing properties of the composites containing activated carbon-fiber felt dipole arrays (ACFFDAs) were investigated. The results show that the absorbing performances of the composites containing ACFFDAs are affected greatly by the dimension parameters of the arrays, the resistance connecting the two arms and the materials of the dipoles. The absorption of the composites containing ACFFDAs presents anisotropy. When the dipoles are parallel to the incident electric field, the composites show better absorbing effect. The absorbing properties rise at first and then fall with increasing the resistance connecting arms or the space between dipoles. In this work, when the dipoles are parallel to the incident electric field, the composite obtains a reflection loss below –10 dB over 12.2 GHz and the minimum value reaches –32 dB. The bandwidth below –10 dB increases with increasing the length of the arms when the dipoles are parallel to the incident electric field. The bandwidth below –10 dB is 13.1 GHz when the length of the arms is 85 mm. Compared with copper plate, the dipole arrays whose arms are made of activated carbon-fiber felt exhibit better absorption properties.

Introduction

With the development of radar, microwave communication technology and especially the need for anti-electromagnetic interference coatings, self-concealing technology and microwave darkrooms, the study of electromagnetic wave absorbing materials has increased in recent years [1–3]. In order to suit the above requirement, many materials have been singled out or synthesized, among them the carbon products have been considering as the most promising candidate since World War II [4–7]. More recently, it has been reported that activation of the carbon fibers can enhance the contribution of multiple reflections for carbon fiber composites [8].

The dipole array, which is a kind of simple antenna array, has been widely employed in radio system, electromagnetic countermeasures, electromagnetic compatibility measurement and other fields. As a receiver, it captures the specific frequency region of electromagnetic waves propagating through space and converts them into voltages and currents in the antenna. If the two arms of the antenna are joined with a resistance, electromagnetic energy is partly transformed into heat energy by the resistance loss, so it is possible to employ the dipole array for attenuation of electromagnetic fields. However, the conventional material for the arms of the dipole (metal) produces strong electromagnetic reflections. This may make the array absorb energy only in a narrow band, which is very disadvantageous for microwave absorption. Therefore, when the dipole array is utilized as the microwave absorbent, its material should be altered.

In this work, activated carbon-fiber felt is used as the material for the arms of the dipole. The selection of the material is based on the following considerations: (i) in the GHz range, electrical properties of activated carbon-fiber felt are similar to those of metal; (ii) activated carbon-fiber felt has the structure of fabrics and

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the fibers composed of it has the irregular-shaped cross sections, which are very advantageous for the absorption of electromagnetic wave [9]; (iii) activated carbon-fiber felt is lighter than metal. To the best of our knowledge, there are no reported experimental results on the design of microwave absorbing materials using an activated carbon-fiber felt dipole array. In this paper, by changing the dimension parameters and the magnitude of the resistance connecting the two arms, different activated carbon-fiber felt dipole arrays (ACFFDAs) were prepared. The experimental evaluation of microwave absorbing materials with ACFFDAs embedded in epoxy resin is presented. The effects of ACFFDAs on the reflection properties are investigated.

Experimental

Materials

The epoxy resin (E-44, Resin company in Wuxi, PRC) used in this study was diglycidyl ether of bisphenol-A (DGEBA), which has an epoxy value of 0.41–0.47 and epoxide equivalent weight near 230. The epoxy resin has the permittivity of 3.0–3.4 and the dielectric loss tangent of 0.01–0.03. The polyamide resin (203$^{\#}$, Chemical plant in Tianjin, PRC) was chosen as the curing agent, which has the permittivity of 3.0–4.0 and the electrical resistivity of 10^{11}–10^{12} $\Omega \cdot$ m. The dielectric properties of both resins are offered by the suppliers. Viscose-based activated carbon-fiber felt (made by Metallography Lab, Tianjin University, PRC) with average thickness of 1.2 mm, average diameter of the filaments of 13–16 μm, the electrical resistivity of ~1500 $\Omega \cdot$ m and the specific surface area of 823 $m^2 g^{-1}$ was used as the material of the arms of the dipole. The copper plate used in this work has the thickness of ~1.2 mm.

Preparation of activated carbon-fiber felt

Viscose-fiber felt (the precursor) activation were conducted by (i) pre-soaking the precursor in an aqueous solution [$NH_4H_2PO_4$ 3 wt.%, $(NH_4)_2SO_4$ 15 wt.%] for the purpose of surface cleansing and improving carbon yields of activated materials, (ii) heating the pre-soaked felt in nitrogen gas (99.99%, 133–266 Pa) to 450 °C at a heating rate of 20 °C/min, (iii) maintaining the temperature at 450 °C for 30 min for the purpose of carbonization, (iv) heating the felt to 950 °C at a speed of 50 °C/min, (v) introducing steam (with a partial pressure of 20%) for 10 min while the temperature remained at 950 °C for the purpose of activation, and (vi) cooling to room temperature.

Preparation of composites

The epoxy resin was blended uniformly with the polyamide resin in the mass ratio of 2:1. After vacuum deformation the mixture was cast into a conventional semi-overflowing die. The ACFFDAs were then put in the middle of the resin mixture. A piece of fiberglass cloth with the same size as the die was laid on the top of the sample in order to make the impedance of the samples well matched with the impedance of air [10]. Molding was carried out in a hydraulic press at 10 MPa pressure and 80 (C for 2 h, obtaining specimens of 180 × 180 mm with thickness of 4 mm for reflectivity measurements. The configuration of the sample is shown in Fig. 1. The ACFFDA is embedded in the middle of the sample and the distance between it and either surface is 2 mm. The pattern of the ACFFDA is shown in Fig. 2, where *L* is the length of the arms, *W* is the width of the arms, *D* is the space between arms and *d* is the interval between dipoles. The two arms are connected using a resistance, which is in the range of 150–1000 Ω. The parameters and the materials of ACFFDAs embedded in the samples are listed in Table 1.

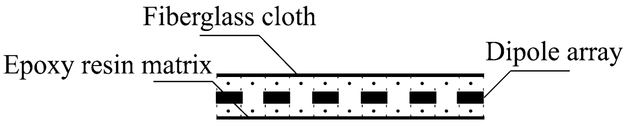


Fig. 1 Cross-section of the sample

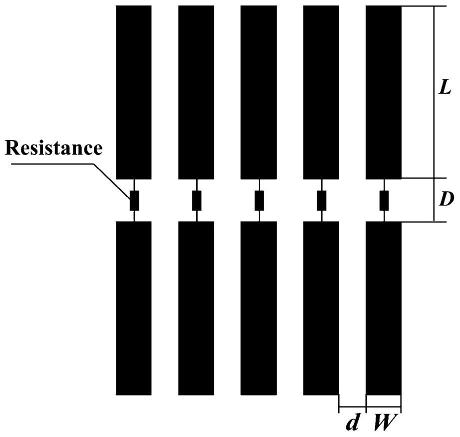


Fig. 2 Geometry of the dipole array made of activated carbon-fiber felt; *L* denotes the length of the arms; *W* denotes the width of the arms; *D* denotes the space between arms; *d* denotes the interval between dipoles

Table 1 The parameters and the materials of ACFFDAs embedded in the samples

No.	L (mm)	W (mm)	D (mm)	d (mm)	Resistance (Ω)	Materials
$1^{\#}$	75	11	20	5	150	Carbon-fiber felt
$2^{\#}$	75	11	20	5	240	Carbon-fiber felt
$3^{\#}$	75	11	20	5	390	Carbon-fiber felt
$4^{\#}$	75	11	20	5	500	Carbon-fiber felt
$5^{\#}$	75	11	20	5	1000	Carbon-fiber felt
$6^{\#}$	75	11	20	3	240	Carbon-fiber felt
$7^{\#}$	75	11	20	8	240	Carbon-fiber felt
$8^{\#}$	75	11	20	11	240	Carbon-fiber felt
$9^{\#}$	75	11	20	14	240	Carbon-fiber felt
$10^{\#}$	65	11	20	5	240	Carbon-fiber felt
$11^{\#}$	70	11	20	5	240	Carbon-fiber felt
$12^{\#}$	80	11	20	5	240	Carbon-fiber felt
$13^{\#}$	85	11	10	5	240	Carbon-fiber felt
$14^{\#}$	75	11	20	5	240	Copper plate

Measurements of microwave absorption

The sample under test was positioned on an aluminum panel (180 × 180 mm). A network analyzer was used to measure the magnitude and phase response of the samples by comparison with the signal transmitted by the samples under test and that reflected from its input. A schematic diagram of the measurement system is given in Fig. 3. The antennas used for the measurements were ridged wideband horns covering the microwave region (2–18 GHz).

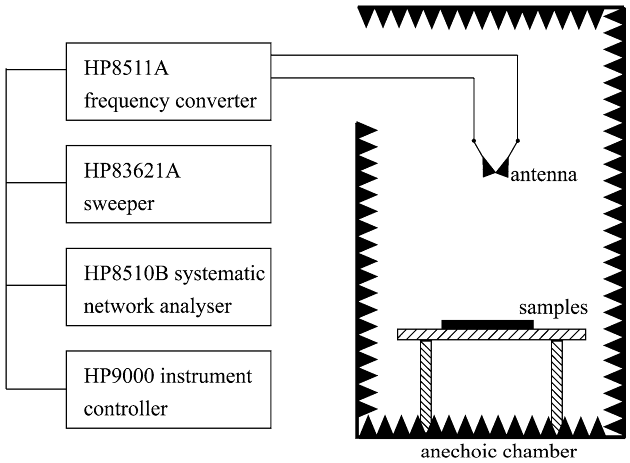


Fig. 3 Schematic diagram of microwave reflectivity measurement system

Results and discussion

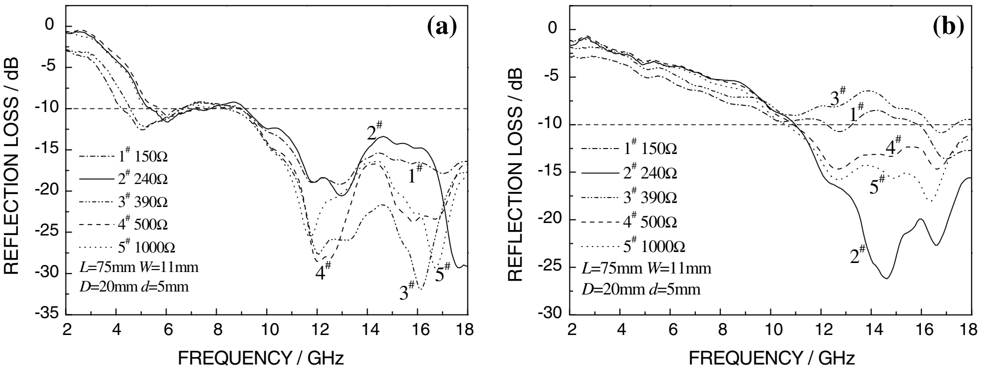
Effect of the resistance on the R.L. of composites

Figure 4 shows the frequency dependence of the reflection loss (*R.L.*) of the composites containing ACFFDAs, where the resistance is taken as a variable, while the others are constants. It can be seen that the magnitude of the resistance influences the *R.L.* of the composites greatly. As shown in Fig. 4a, when the dipoles are parallel to the incident electric field, the minimum *R.L.* decreases and the bandwidth below –10 dB increases while the resistance increases from 150 to 390 Ω. As the resistance is 390 Ω (sample $3^{\#}$), the *R.L.* is below –10 dB in the bandwidth of 12.2 GHz, and the minimum value is –32 dB at 16.1 GHz. After that, with the resistance continuing to rise, the absorbing effect of the composites begins to fall. Obviously, the optimum *R.L.* is corresponded to a suitable magnitude of the resistance, which is 390 Ω in this case. It can be seen from Fig. 4b that when the dipoles are perpendicular to the incident electric field, the resistance changes the absorbing properties in a similar way as they are parallel to the incident electric field. As the resistance is 240 Ω (sample $2^{\#}$), the best absorbing performance is obtained, with the maximum absorption of –26.3 dB and the bandwidth below –10 dB of 7.2 GHz.

For all the samples, when the dipoles are parallel to the incident electric field, in the frequency range of 5–9 GHz, the *R.L.* of the samples fluctuates around –10 dB. As the frequency is higher than 9 GHz, the *R.L.* is below –10 dB all along. But when the dipoles are perpendicular to the incident electric field, the *R.L.* is below –10 dB only in the frequency region higher than 10.5 GHz. That is to say, the absorption of the composites containing ACFFDAs presents anisotropy.

The dipole array has the properties of polarization. That means it only captures the specific frequency region (which is called the operating band) of electromagnetic wave and transfers it into high-frequency voltages and currents in the dipoles. Therefore, the electromagnetic energy is partly transformed into heat energy by the resistance of the carbon-fiber felt and the resistance connecting the two arms of the dipole. This may be the reason that hollows occur in the absorption curves of all the samples. When the incident electric

Fig. 4 The effect of the resistance connecting the two arms of the dipole on the reflection loss. (**a**) the dipoles are parallel to the incident electric field; (**b**) the dipoles are perpendicular to the incident electric field



field is parallel to the dipoles, it excites strong magnitude of currents in the dipoles, which leads to rapid attenuation of incident electromagnetic fields. However, as the incident electric field is perpendicular to the dipoles, much weaker currents are excited than it is parallel to the dipoles [11], as a result the microwave enters the composite and reflects off with little absorption. That is the reason for the anisotropy of the microwave absorption.

When the resistance connecting the arms of the dipole is too small, the resistance loss is too much small to consume incident electromagnetic energy effectively, resulting in an increase in the *R.L.* values. On the contrary, when the resistance is too big, no continuous currents are in the dipoles and the dipole array exhibits poor absorbing behavior. Obviously, the optimum microwave absorption corresponds with the moderate magnitude of resistance (which is well consistent with the experimental results). In above experiments, when the incident electric field is parallel and perpendicular to the dipoles, the optimum magnitude of resistance is 390 and 240 Ω, respectively.

Effect of *d* values on the R.L. of composites

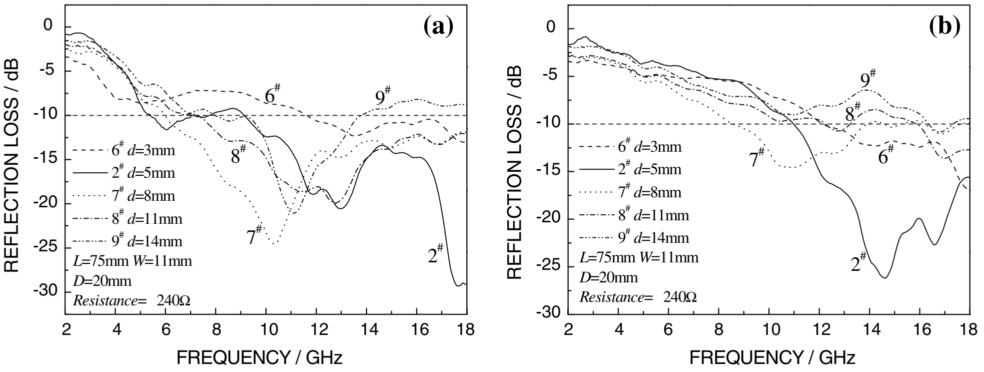
Figure 5 shows the absorption curves of the samples containing ACFFDAs, where *d* is taken as a parameter. As can be seen from Fig. 5, when the dipoles are parallel to the incident electric field, samples present better absorption characteristics as compared with those perpendicular to the incident electric field. Whether the dipoles are parallel or perpendicular to the incident electric field, with reducing *d* value, the absorption performances have the similar trend, that is, they exhibit the optimum absorbing property at an intermediate *d* value. As can be seen from Fig. 5, while $d = 5$ mm, the absorption effect reach the optimum.

Assume that there are *N* dipoles in the array and the space between dipoles is *d*. The tie line of the middles of the dipoles is set as the x direction (see Fig. 6). The magnitude of the induced currents in each dipole is the same, and the phase shift is progressive. The point P is random and far away from the array (the distance between P and the array $r \gg d$).

Consider the electric field intensity corresponding to the dipole 1 is $\vec{E}_0$ at the point P and take $\vec{E}_0$ as a reference, the total elctric field intensity $\vec{E}$ of the array is expressed as [11]

$$\begin{aligned}\vec{E} &= \vec{E}_0 + \vec{E}_1 + \vec{E}_2 + \cdots + \vec{E}_{N-1} \\ &= \vec{E}_0\left[1 + e^{j\psi} + e^{j2\psi} + \cdots + e^{j(N-1)\psi}\right]\end{aligned} \tag{1}$$

Fig. 5 The effect of the space between dipoles on the reflection loss. (**a**) the dipoles are parallel to the incident electric field; (**b**) the dipoles are perpendicular to the incident electric field



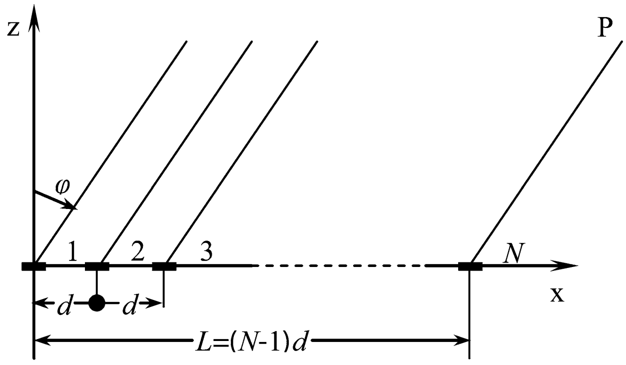


Fig. 6 Model of the dipole array

$$\left|\vec{E}\right| = \left|\vec{E}_0\right| \bullet \frac{\sin\frac{N\psi}{2}}{\sin\frac{\psi}{2}} = \left|\vec{E}_0\right| \bullet f_n(\psi) \qquad (2)$$

where $\psi = kd\sin\varphi$ (k is the wave number), the array pattern $f_n(\psi) = \frac{\sin\frac{N\psi}{2}}{\sin\frac{\psi}{2}}$. Equation (2) indicates that $\left|\vec{E}\right|$ increases with reducing d, namely, the absorbption effect rises with the decrease of d. However, with the increase of the dipoles in the array, the content of carbon-fiber felt in the composites increases, resulting in the samples gradually presenting strong reflection characteristics. Therefore the space between dipoles has the optimum value.

Effect of *L* values on the R.L. of composites

The microwave absorption characteristics of the samples with different *L* values are shown in Fig. 7. As can be seen from Fig. 7a, when the dipoles are parallel to the incident electric field, the beginning frequency of the band below –10 dB moves toward low frequencies for about 1 GHz with increasing *L* from 65 to 85 mm. While *L* = 85 mm, the beginning frequency reaches 4.9 GHz and the bandwidth below –10 dB is over 13.1 GHz. It can be observed from Fig. 7b that when the dipoles are perpendicular to the incident electric field, the composites present good absorbing performances only at high frequencies. When *L* = 70 mm, the bandwidth below –10 dB is 8.3 GHz.

According to the electromagnetic field theory [12], the maximum operating band of the dipole can be approximately expressed as

$$(f_{\max} - f_{\min})/f_{\min} = \Delta f/f_{\min} \approx kL/2a_e \qquad (3)$$

where k is the constant, L and a_e are the length and the equivalent radius of the arms respectively. From Eq. (3), it is obvious that the operating band (the absorbing bandwidth) rises with increasing the length of the arms.

Effect of the materials of the arms on the R.L. of composites

In order to evaluate the effect of the materials for the dipole arms on the absorbing properties, the composites containing the dipole arrays whose arms are made of copper plate were also prepared. Figure 8 shows the comparison between the *R.L.* of the composites containing ACFFDSs and that of the ones containing the copper plate dipole arrays. It can be observed that compared with the latter, the composites containing ACFFDAs present better absorbing properties, while the dimensions of the arrays keep unchangeable. When the dipoles are parallel to the incident electric field, the maximum absorption of sample 14$^{\#}$ is –8.1 dB at 13.1 GHz. But the maximum absorption of sample 2$^{\#}$, in which the activated carbon-fiber felt was adopted as the material of the dipole arms, reaches –30 dB at 17.3 GHz and the bandwidth below –10 dB of about 12 GHz is obtained. On the other hand, when the dipoles are perpendicular to the incident electric filed, sample 14$^{\#}$ presents a little absorbing value. But for sample 2$^{\#}$ the *R. L.* is still less than –10 dB in the frequency range from 11 to 18 GHz. These differences may be attributed to the alteration of the material of the

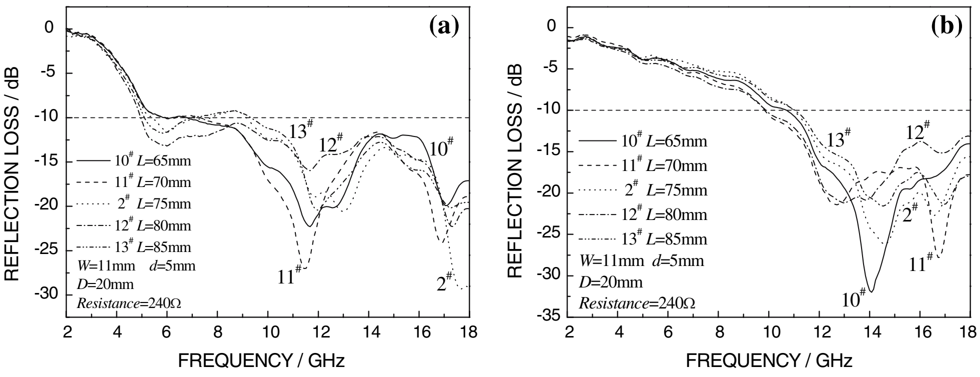


Fig. 7 The effect of the length of the arms of the dipole on the reflection loss. (**a**) the dipoles are parallel to the incident electric field; (**b**) the dipoles are perpendicular to the incident electric field * While *L* = 85 mm, *D* = 10 mm

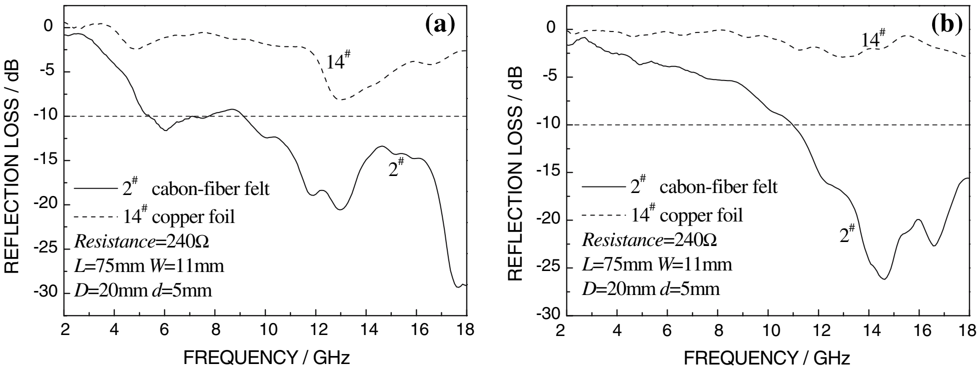


Fig. 8 The effect of the materials of the dipoles on the reflection loss. (**a**) the dipoles are parallel to the incident electric field; (**b**) the dipoles are perpendicular to the incident electric field

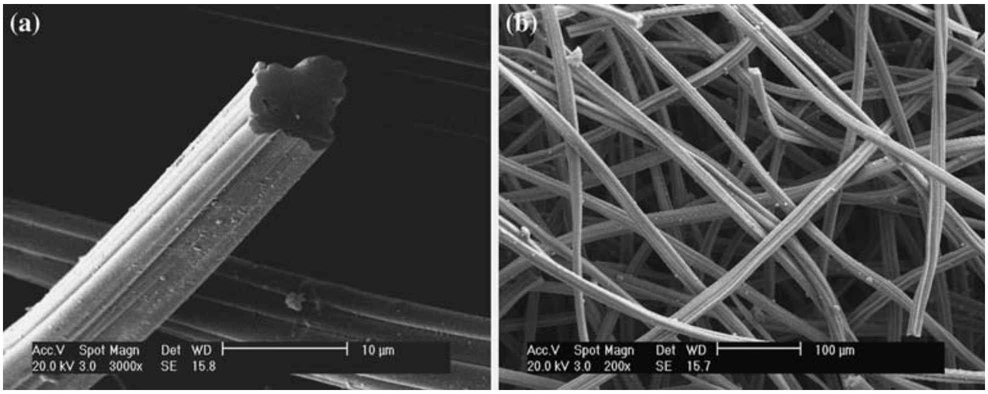


Fig. 9 SEM photographs of viscose-based activated carbon-fiber felt

dipole arms. This also suggests that by using the activated carbon-fiber felt as the material of the dipole arms, the anisotropy to the incident electromagnetic wave is weakened.

The cross-sections of carbon fibers in the felt are irregular-shaped and their surface grooves are quite obvious as shown in Fig. 9. The activated carbon-fiber felt composed of these fibers has the structure of three-dimensional fabrics. The structure is like that of microwave anechoic chamber, where there are many small pyramids [9]. When incident wave arrives at the activated carbon-fiber felt, it is multi-reflected and gradually attenuated. Moreover, the intrinsic impedance of the composites containing ACFFDAs are much closer to that of the free space than those containing the copper plate dipole arrays and therefore, it is more advantageous for the electromagnetic wave to propagate into the absorbing materials containing ACFFDAs and to be attenuated.

Conclusions

In this paper, microwave absorbing properties of the composites containing activated carbon-fiber felt dipole arrays (ACFFDAs) were investigated. The results are briefly summarized as follows.

(1) The microwave absorption of the composites containing ACFFDAs presents anisotropy. When the dipoles are parallel to the incident electric field, the composites show better absorbing performances.
(2) The absorbing properties of the composites containing ACFFDAs rise at first and then fall with increasing the resistance connecting arms or the space between dipoles. That means the resistance and the space have the optimum values respectively.
(3) When the dipoles are parallel to the incident electric field, the bandwidth below –10 dB increases with increasing the length of the arms.
(4) Compared with copper plate, the composites containing the dipole arrays whose arms are made of the activated carbon-fiber felt exhibit better absorption effect.

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