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Effects of heat treatment temperature on microstructure and electromagnetic properties of ordered mesoporous carbon

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Abstract: Ordered mesoporous carbon (OMC) powder was synthesized through template method to investigate its potential as an effective light weight electromagnetic interference (EMI) absorber in the frequency range of 8.2-12.4 GHz (X band). OMCs were heat-treated at 1400 °C, 1600 °C and 1800 °C, respectively, in nitrogen atmosphere for 2 h. The microstructures of the OMCs before and after heat treatment were studied. The dielectric property of the as-received OMC powders was measured. The average loss tangent (tan δ) of samples made from OMC powder heat-treated at 1400 °C was as high as 3.1, much higher than that of the sample made from OMC without heat treatment. Shielding mechanism was studied by resolving the total shielding effectiveness (SE) into absorption and reflection. Samples made from OMC powders heat-treated at 1400 °C and 1600 °C exhibit an EMI shielding behavior dominated by electromagnetic absorption mechanism, implying its promising perspective as electromagnetic wave absorbers. **Key words:** ordered mesoporous carbon; electromagnetic (EM) wave absorber; heat treatment; dielectric property; electromagnetic interference (EMI) shielding effectiveness

1 Introduction

For the protection of environment and sensitive circuits from the electromagnetic (EM) radiation emitting from telecommunication apparatus, a variety of research works have been carried out to investigate the electromagnetic interference (EMI) shielding and EM wave-absorption properties of materials in recent years. Metals were traditional EMI shielding material and functions mainly by reflection, which limits their applications where EM absorption is required (e.g., in stealth technology). The EM wave absorption capability of a material is related to its shape [1], nature [2], and size [3]. Therefore, materials with ohmic and dielectric losses to EMI waves, orderly arrangement or with nanostructures, such as ferrites, carbon nano-tubes (CNTs), ZnO nanostructures [4,5], SiC nano-wires [6], BaTiO₃ ferroelectric ceramics [7], carbon nanocoils [8] and carbon fibers [9], have been extensively studied. Most of them are acting as absorbers and are dispersed in the insulating matrix, which forms a structure that EM waves may easily enter the material and interact with the absorbers [10,11].

Carbon materials, especially nanostructure carbon materials, have attracted most attention as EM wave absorbers, due to their comparatively high conductivity, low weight, good EM absorption property, flexibility, and environmental and thermal stabilities [1-3]. For example, polymer composites that contain carbon and CNT-based fillers have been widely explored and found to be useful EMI shielding or EM wave absorbing materials [12]. ZrO₂-embedded carbon fibers were prepared by electro-spinning and heat treatment methods for the use as an EMI shielding material. The best efficient EMI shielding effectiveness (SE) in 800-8500 MHz was around 31.8 dB [13]. The EMI SE of graphene/epoxy composites on graphene-based sheets was studied, and the highest EMI SE of the composites containing 15% solution-processable functionalized graphene was 21 dB in X-band [14]. Electrospun fiber sheets embedded fluorinated carbon black were studied, and a high EMI SE of 50 dB was obtained after the fluorination of carbon black [15]. A new type of thin and

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flexible CNT-polymethylmethacrylate film was synthesized, which has a high EMI SE of 27 dB when the content of CNT is 40% in volume fraction [16].

Recently, regularly arrayed mesoporous carbons have been synthesized [17] and studied. Among them, the self-ordered mesoporous carbon (OMC), first reported in 1999 through carbonizing sucrose inside the pores of the self-ordered mesoporous silica template, attracted much attention [18] because of their remarkable physico-chemical properties, such as good mechanical stability, unique electrical behavior, and special nanostructure composed of ordered nano-pipe arrays. It is considered prosperous in applications as methane and hydrogen storage, electrochemical double-layer capacitors, catalyst supports and EMI absorbers [19].

OMC/fused silica composite was successfully synthesized. The EMI SE of an OMC/fused silica composite containing 10% OMC was as high as 40 dB in the X-band, which was higher than that of CNT/fused silica composite with the same carbon content (30 dB). This indicates that conductive OMC/fused silica composites are suitable for the application as EMI shielding materials [12].

However, up to now, literatures on the intrinsic dielectric properties of OMCs can seldom be found, and the EMI shielding mechanism of OMC is still little studied. In the present work, we aim to do some detailed investigation on the dielectric properties and EMI shielding properties of the OMC. Herein, one kind of hexagonal self-ordered mesoporous carbon (CMK-3) was prepared using hexagonal mesoporous silica (SBA-15) as a template. The as-received OMCs were heat-treated at 1400, 1600 and 1800 °C, respectively, and the powders acting as EM wave absorbers were dispersed into paraffin acting as insulating matrix. The dielectric properties and EMI shielding properties of the as-received composites were studied over X-band.

2 Experimental

2.1 Materials

The starting powders were commercially available as pure SBA-15, with pore diameter of 8–9 nm. The SBA-15 was calcined at 550 °C for 2 h in air. The calcined SBA-15 (1 g) was mixed with an aqueous solution (5 mL) of sucrose (1.25 g) and H₂SO₄ (0.14 g). The resulting slurry was placed in an oven at 80 °C for 6 h, followed by further treatment at 160 °C for 6 h. In order to obtain fully polymerized and carbonized sucrose inside the pores of silica SBA-15 template, additional sucrose (0.8 g), H₂SO₄ (0.09 g), and water (5 g) were added to the pretreated sample and the mixture was again subjected to the thermal treatment described above. Carbonization was completed by pyrolysis at 900 °C in Ar atmosphere, yielding the CMK-3/SBA-15 composite powder. The carbon-silica powder obtained after pyrolysis was washed with 5% hydrofluoric acid at room temperature for 24 h, to remove the silica template. The template-free carbon product thus obtained was filtered, washed with ethanol, and dried at 120 °C. According to the study conducted by JUN et al [20], that the silica content in the product was normally less than 5% after the first washing with the HF solution, and the second washing gave only traceable amount of silica.

2.2 Sample preparation

The OMC obtained at 900 °C was then heat-treated at 1400, 1600, and 1800 °C in nitrogen atmosphere for 2 h. In order to measure the complex permittivity of the as-prepared and heat-treated OMC powders, they were dispersed in molten paraffin, and then the mixtures were poured into a standard copper flange (22.86 mm×10.16 mm×2.86 mm) in liquid state. In order to minimize the testing error caused by gaps between the samples and the flange, the samples were then clamped tightly between two coaxial waveguide cavities with the flange. During the discussion of influence of heat treatment temperature on EMI shielding property of OMC, the contents of both original and heat-treated OMC powders in the OMC/paraffin samples were 40%. The paraffin used had a constant permittivity of $\varepsilon' = 2.23 - 2.27$ and $\varepsilon'' = 0 - 0.01$ in X-band.

2.3 Characterization

H–9000 high-resolution transmission electron microscope (HRTEM; Technai F30, FEI company, America, acceleration voltage: 300 kV) was used for the morphology and selected area electron diffraction (SAED) analysis of OMC. The measurements of complex permittivity (ε' , ε'') and *S* parameters were conducted with a network analyzer (VNA, MS4644A, Anritsu, Japan). The phase identification of the samples was detected by an X-ray diffractometer (XRD) with Cu K_a radiation (X'pert Pro, Philips, Netherlands) and performed by large angle scattering XRD and small angle X-ray scattering (SAXS), respectively.

3 Results and discussion

3.1 Phase composition and microstructure of OMC

In order to study the effect of heat treatment on microstructure and phase composition of OMC, the prepared OMC powders were heat-treated at 1400, 1600, and 1800 °C for 2 h, respectively. Figures 1(a) and (b) show SAXS and powder XRD patterns of OMC, respectively.

During the synthesis of OMC, carbon converted from sucrose was originally coated on the pore surface of calcined SBA-15 template. The removal of the template resulted in pipe-like mesoporous carbon. Those nano-pipes were rigidly interconnected into a highly ordered 2D hexagonal *P6mm* space group, giving rise to the (100) SAXS peak [21]. Heat treatment led to the reduction of interplanar spacing of the graphite carbons and further caused a portion of adjacent pipes to debond and carbon pipe-walls started to curve. As a result, the intensity of SAXS pattern decreased after heat treatment at 1400 °C. Heat treatment at 1600 °C led to an even larger degree of crystallization, and the SAXS turned featureless, implying the disappearance of ordered structure after heat treatment.

In Fig. 1(b), broad (002) diffraction peaks were observed in all four diffraction patterns of OMC powders. With the increase of heat treatment temperature, (002) diffraction peak slightly shifted to large angle, which indicates the decrease of interplanar spacing and the increase of graphitization degree of these carbons. The interplanar spacing (d_{002}) was determined from the position of each refined (002) peak, according to the Bragg formula ($2d\sin\theta=\lambda$) [22], as listed in Table 1. With the increase of the heat treatment temperature, peak (002) of OMC powders slightly shifts in the direction of higher



Fig. 1 XRD patterns of heat-treated OMC at small scattering angles (a) and large scattering angles (b)

 Table 1 Interplanar spacing of OMC powders heat-treated at different temperatures

Heat treatment temperature/°C	Interplanar spacing/nm
Room temperature	0.394
1400	0.385
1600	0.365
1800	0.346

 2θ , suggesting the decrease of lattice constant of graphite carbon due to the decrease of interplanar distance according to the Bragg formula. These interplanar spacing values were much larger than those of graphite (d_{002} =0.3354 nm), indicating a low graphitization degree of these carbons.

Heat treatment at 1800 °C brought the largest crystallization degree to OMC, which can be known from the narrowest (002) diffraction peak and the increase of (100) diffraction peak. The XRD peaks of the OMC powders do not increase at large scattering angles after heat treatment at 1400 °C and 1600 °C. However, the amorphous peaks at around 22° shown in Fig. 1(b) and ring patterns in the SAED pattern shown in Figs. 2(a) and (c) imply the existence of graphite carbon and OMC is partially crystallized.

Figure 2(a) shows the TEM image of OMC directly synthesized from SBA-15. The image was taken perpendicularly to the direction of the hexagonal pore arrangement of CMK-3. As shown in Fig. 2(b), high-resolution TEM (HRTEM) image exhibits ordered arrangement of the carbon nano-pipes with diameter of 8-9 nm (similar to that of SBA-15), which indicates the basic structure of OMC. In the inset of Fig. 2(a), the SAED pattern of OMC shows the existence of the crystal planes (100) and (110) of graphite carbon, with only traceable intensity, implying the low graphitization degree of OMC. The image in the inset of Fig. 2(b) shows the fringe of one OMC particle, which exhibits the feature of amorphous carbon. After heat treatment, the walls of carbon nano-pipes in OMC turned slightly curving, as shown in Fig. 2(c), and the ordered nano-pipe arrays turned rough, not as parallel as that shown in Fig. 2(a). In the inset of Fig. 2(c), the SAED pattern is similar to that of OMC before heat-treatment, except for stronger and sharper diffraction rings of crystal planes (100) and (110), indicating the increased crystallization degree of carbon in OMC. Figure 2(d) shows the fringe of one OMC particle heat-treated under 1600 °C, which exhibits a clear layer-structure, tangling and weaving with each other.

Figure 3 shows the schematic drawing of the microstructure evolution of OMC in one unit during synthesis and heat treatment procedure. The ordered mesoporous silica (SBA-15) was used as the solid



Fig. 2 TEM image of OMC powder directly synthesized from SBA-15 and corresponding SAED pattern (inset) (a), HRTEM image of OMC powder directly synthesized from SBA-15 (b), TEM image of OMC powder heat treated at 1600 °C and corresponding SAED pattern (inset) (c) and HRTEM image of OMC powder heat-treated at 1600 °C (d)



Fig. 3 Schematic drawing of micro-structural change of OMC during synthesis and heat treatment procedure: (a) SBA-15 template; (b) In-situ filling of mesopores in SBA-15 with carbon; (c) OMC obtained after removal of SBA-15 template; (d) Heat treatment at 1400 °C and 1600 °C leading to curve of carbon nano-pipe walls of OMC; (e) Heat treatment at 1800 °C leading to collapse of ordered structure of mesopores

template and filled with carbon following the experimental procedure described above. Then the SBA-15 silica template was removed and OMC was obtained. The as-sintered OMC was then heat-treated. After heat treatments at 1400 °C and 1600 °C, the

cylindrical wall of regularly arrayed carbon nano-pipes in OMC turned curving. However, heat treatment at 1800 °C caused the destruction of the ordered structure of OMC, owing to the significant increase of crystallization degree.

3.2 Effects of heat treatment temperature on permittivity

Generally, the complex relative permittivity ε of materials is known as

$$\varepsilon = \varepsilon' + j\varepsilon''$$
 (1)

and the dielectric loss tangent is

$$\tan \delta = \varepsilon'' / \varepsilon' \tag{2}$$

They are the greatest important material properties for the interaction to EM wave of a dielectric material [22]. The real part (ε') correlates with polarization, and the imaginary part (ε'') represents conductive loss; the dielectric loss tangent (tan δ) predicts the ability of the material to convert the absorbed electromagnetic energy into heat [23].

The real and imaginary permittivities of the samples are shown in Figs. 4(a) and (b). For samples made from OMC before heat treatment, average values of real and imaginary permittivity were 9.9 and 6.5, respectively. After heat treatment at 1400 °C, average real permittivity of the samples was 16.8, increased by 1.7 times. As real permittivity correlates with polarization degree of the material [22], the result indicates that polarization of the material was improved significantly after heat treatment at 1400 °C. Heat treatment at 1600 °C brought less change to the real permittivity of OMC/paraffin sample, except for an obvious resonance at 10.2-11.8 GHz. Heat treatment at 1800 °C seldom brought any change to the real permittivity of OMC/paraffin sample, indicating no improvement of polarization to OMC. Similar to the real permittivity, after heat treatment at 1400 °C, the imaginary permittivity of the samples increased by almost 8.0 times. Imaginary permittivity related to the dissipation of energy in the material [24]. Therefore, our results suggest that the OMC powders heat-treated at 1400 °C may have the greatest EMI SE because the applied electromagnetic waves were attenuated through the emission of heat energy. Additionally, both the real and imaginary permittivities decreased with increasing the applied frequency because the dipole moments in the carbon could not reorient themselves along the direction of the applied electric field at high frequencies [24].

Figure 4(c) shows the dielectric loss tangent of OMC/paraffin samples. The samples made from original OMC powders had a dielectric loss tangent of around 0.7. It is noteworthy that after heat treatment at 1400 °C, the value of dielectric loss tangent of OMC/paraffin sample was over 2.3, with an average value of 3.1. After heat treatment at 1600 °C, although the resonance of real permittivity of OMC/paraffin sample had an obvious shift in the frequency range between 10.2 and 11.8 GHz, dielectric loss tangent of the samples was still over 1.9 and the average loss tangent was 3.2.



Fig. 4 Real permittivity (a), imaginary permittivity (b) and dielectric loss tangent (c) of OMCs/paraffin composites with 40% OMC in X-band

Dielectric loss tangent is an important factor that affects the EMI shielding mechanism of a material. This quantity is a measure of dielectric loss in a material for a given sample thickness at a specified wavelength and is directly related to the attenuation factor that determines the attenuating property of the material [25]. The attenuating property improves as the dielectric loss tangent increases, which is due to a higher attenuation factor [25]. ΕM wave absorbers usually have comparatively high dielectric loss tangent. The microwave attenuation capability of polymer derived SiC

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ceramics were significantly improved through heat treatment procedure at 1500 °C, for the great improvement of its dielectric loss tangent [26]. Al-doped β -SiC/paraffin sample with the volume ratio of SiC powders to paraffin wax of 1:1.5, and thickness of 3 mm had the highest dielectric loss tangent up to 0.7 and imaginary permittivity of around 20 in X-band [27]. The dielectric loss tangent of MWCNT/epoxy composites with mass concentrations up to 11.4%, 1 mm in thickness, is around 0.4 in X-band [28]. Carbon black/paraffin sample containing 80% carbon black has a dielectric loss tangent of around 1.5 within the frequency range of 2-18 GHz [29]. These materials are all typical EM wave absorbers and are extensively studied. Compared with these materials, OMC has a comparatively high dielectric loss tangent and preferable EMI shielding property, as reported in the work of OMC/fused silica composites [12]. Heat treatments at 1400 °C and 1600 °C then brought significant improvement to its dielectric loss tangent, therefore made it an excellent candidate as EMI wave absorber, with good attenuating properties.

These conspicuous responses of OMC to electromagnetic wave were attributed to microstructure change of OMC brought by heat treatment at different temperatures. Heat treatment at 1400 °C led to graphitization in amorphous OMC. With the decrease of crystal plane, the cylindrical wall of regular arrayed carbon nano-pipes in OMC turned curving. The microstructure change increased the capability of OMC to constrain electromagnetic wave to enter their mesopores. The slight deformation caused by heat-treatment also increased the connectivity among carbon nano-pipes in OMC particles. The OMC powders studied in the present work may exhibit metallic character [20]. The motion of the conducting electrons leads to high electric loss [21]. These factors together led to the increase of imaginary permittivity compared with the original OMC samples. As a result, OMC powders heat-treated at 1400 °C and 1600 °C have excellent EM wave attenuation properties. However, heat-treatment at 1800 °C with more graphitization degree was not able to bring better dielectric property of OMC. Although graphite and OMC are allotropic forms of carbon, their different structures in macro- and micro- structure determine that the excessive generation of graphite in OMC would be counterproductive to its EM wave absorption property. Graphite is continuous two-dimensional conductor whose main EM wave absorbing mechanism is resistance loss. However, its high conductivity would cause strong reflection to the incident wave. As a result, the abundance of graphite is detrimental to the EM wave absorption property of an EMI shielding material. When it comes to OMC, the EM wave absorbing mechanism is a combination of resistance loss and dielectric loss. The ordered 2D hexagonal P6mm space group of OMC increased the capability to constrain electromagnetic wave to enter their mesoporous, lengthen EM wave propagating path and increase the possibility for the incident EM wave to be completely absorbed. What's more, OMC is made of amorphous carbon, whose conductivity is poor compared with graphite. Their molecular fragments of the graphite layer structures are irregularly arranged, containing the microcrystalline structures with a large number of defects, which could effectively attenuate EM waves. Heat-treatment improved its crystallization degree, some graphite grains generated in the amorphous carbon. When EM wave enters OMC particles, it will first be attenuated by amorphous carbon, then meet graphite grain and change propagating path. The multiple reflections caused by the generation of graphite after heat-treatment also lengthen EM wave propagating path and enhance the attenuating effect of OMC to EM wave. These two factors work together and make OMC a good EM wave absorber. Heat treatment under 1800 °C led to a greater proportion of graphitization, and caused the collapse of the ordered mesoporous structure of OMC. As a result, both the real and imaginary permittivities of OMC powders heat treated at 1800 °C stayed at low levels.

Higher ε' and ε'' mean more bound electrons. Under the alternating electromagnetic field, these bound electrons migrate to and fro to form relaxation polarization and dissipation, thus resulting in higher ε' and ε'' [30] and better EMI shielding performance, which will be discussed in the following text.

3.3 EMI shielding effectiveness of OMC

The absorption coefficient and the shielding efficiency of OMC/paraffin samples were calculated using S-parameters. The S-parameters, S_{11} , S_{12} , S_{21} and S_{22} , were obtained during the measurement of the complex permittivity. Reflection coefficient, R, and transmission coefficient, T, are given as [31]

$$R = |S_{11}|^2 = |S_{22}|^2, \quad T = |S_{21}|^2 = |S_{12}|^2$$
(3)

The absorption coefficient, A, is obtained from the simple relation:

$$A + R + T = 1 \tag{4}$$

The transmittance T is the ratio of $P_{\rm T}$ to $P_{\rm I}$, the power (electric field) of incident and transmitted EM waves, respectively [32]:

$$T = (P_{\rm T}/P_{\rm I}) = (E_{\rm T}/E_{\rm I})^2$$
(5)

Thus, the shielding effectiveness SE_{total} of shielding material can be written as

$$SE_{total} = 20lg(E_I/E_T) = -10lgT$$
(6)

The SE_{total} is the summation of the SE due to absorption (SE_A), reflection (SE_R), and multiple reflections (SE_M) [33],

$$SE_{total} = SE_A + SE_R + SE_M$$
(7)

When $SE_{total} > 15 \text{ dB}$, SE_M is negligible. Equation (7) is usually expressed as

$$SE_{total} \approx SE_A + SE_R$$
 (8)

Considering the effective absorbance (A_{eff}) , which is defined as $A_{\text{eff}}=(1-R-T)/(1-R)$ with respect to the power of the incident EM wave inside the shielding material, the SE due to reflectance and effective absorbance can be described as [34]

$$SE_{R} = -10lg(1-R) \tag{9}$$

$$SE_{A} = -10lg[T/(1-R)]$$
 (10)

In the present study, Eqs. (9) and (10) are used to determine the contribution of absorption and reflection loss to SE_{total} . Figure 5 shows the SE_{total} of our various samples, which is divided in proportion of SE_A and SE_R .



Fig. 5 Contribution of reflection and absorption to EMI SE of OMCs/paraffin samples containing 40% OMC heat-treated at different temperatures

As expected from the variation trends of the real and imaginary parts of permittivity of samples shown in Fig. 4, SE_{total} of the sample containing OMC powders heat-treated at 1400 °C was the highest, with an average value of 30.5 dB, which was 3.8 times higher than the SE_{total} of the sample containing the original OMC. The higher value of SE_{total} may be attributed to the unique structure of the hexagonal carbon nano-pipe arrays. At the same time, heat treatment introduced a great deal of defects and microcrystals in the ultra-thin OMC mesoporous walls (3 nm), which was also in favor of improving the overall EMI SE of heat-treated OMC samples [35]. From a commercial perspective, the target EMI SE value for applications is around 20 dB, which means that 99% of incident EM wave can be blocked [15]. After heat treatment at 1600 °C, SE_{total} of the sample stayed over 24 dB. Heat treatment at 1800 °C seldom brought improvement to SE_{total} of OMC/paraffin sample for the structure order of OMC totally destructed.

After heat treatments at 1400 °C and 1600 °C, SE_A increased significantly. For the sample prepared from OMC powders heat-treated at 1400 °C, SE_A takes 78.9% of SE_{total}, with an average value of 24.0 dB. For OMC heat-treated at 1600 °C, the SE_{total}, SE_A, and SE_R are 26.2, 22.1, and 4.1 dB on average, respectively, in which SE_A takes 84.4% of SE_{total}. However, heat treatment at 1800 °C seldom brought change to the SE of OMC/paraffin sample and SE_A only takes 56% of SE_{total} on average.

The above results indicate that heat treatment at 1400 and 1600 °C effectively improved the total EMI SE of OMC powders. The increasing rate of the EM wave absorption was much higher than that of EM wave reflection, because of moderated conductivity of heat-treated OMC. Heat-treated OMC powders at 1400 °C and 1600 °C displayed excellent EMI SE, which is suitable for the use in EMI shielding or EM absorption materials in the microwave frequency range. This result is consistent with the varying trend of imaginary permittivity and dielectric loss tangent.

As the OMC powders heat-treated at 1400 °C had a superior overall performance, they were chosen to demonstrate the variation trend of SE_{total} , SE_A and SE_R in X-band as a function of OMC content (%). As shown in Fig. 6, with increasing OMC content, both SE_A and SE_R increased, but the increasing rate of SE_A is much higher than that of SE_R . Results show that absorption became the major contributor to the total EMI SE when the content is above 10%. For the sample with 40% OMC, SE_{total} , SE_A , and SE_R are 30.4, 24.0, and 6.4 dB, respectively. The contribution of the absorption (SE_A) to the total EMI SE is approximately six times larger than that of the reflection (SE_R). The above analysis results



Fig. 6 Comparison of SE_{total} , SE_A and SE_R of OMCs/paraffin samples containing different contents of OMC powders heat-treated at 1400 °C

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show that absorption is the main EMI shielding mechanism.

4 Conclusions

1) OMC was successfully synthesized through template method.

2) The OMC heat-treated at 1400 °C with partially crystallized carbon has the highest permittivity. The real permittivity increases by 1.7 times and the imaginary permittivity increases by 8.0 times after heat treatment at 1400 °C, resulting in the highest SE_{total} of around 30.5 dB in X-band. The dielectric loss tangent of OMC/paraffin powers after heat treatment significantly increases from 0.7 to 3.1.

3) For the sample with OMC content of 40%, the contribution of the absorption (SE_A) to the total EMI SE is approximately six times larger than that of the reflection (SE_R). The EMI shielding mechanism of carbon is dominated by the absorption of electromagnetic waves with the increase of OMC content.

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热处理温度对有序介孔碳微结构和 电磁屏蔽性能的影响

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摘 要:通过模板法制备了有序介孔碳(OMC),研究了有序介孔碳粉体在 8.2~12.4 GHz (X 波段)范围内作为轻质 电磁波吸收剂的电磁屏蔽性能。在氮气保护的条件下对 OMC 粉体分别在 1400、1600 和 1800 °C 进行 2 h 热处理。 研究了热处理前后 OMC 微结构的变化,并测试了所得 OMC 粉体的介电常数。在 1400 °C 下热处理所得 OMC 粉 体试样的损耗正切(tan δ)高达 3.1,远远高于未进行热处理的 OMC 试样的。通过将总的屏蔽效能分解为吸收和反 射两部分,研究了 OMC 试样的电磁屏蔽效能。于 1400 °C 和 1600 °C 热处理后,OMC 得到最高的电磁屏蔽效能 其屏蔽机制以吸收为主,表明 OMC 具有作为微波吸收剂的潜力。

关键词: 有序介孔碳; 电磁波吸收剂; 热处理; 介电性能; 电磁屏蔽效能

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