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Investigation of Electromagnetic Shielding Effectiveness of Nanostructural Carbon Black/ABS Composites

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ABSTRACT

With the increasing application in electromagnetic interference shielding field of high polymer materials, there is an increasing interest in investigating of high polymer composites. The effects of carbon black fraction on volume resistivity and electromagnetic shielding effectiveness (SE) of nanostructural carbon black (CB)/Acrylonitrile Butadiene Styrene (ABS) composites were studied. The results indicated that when CB mass fraction was over 15%, *the volume resistivity dropped sharply and when it rose to* 35%, *the volume resistivity achieved the lowest value* 103 *Ω·cm and the SE was about* 6 *dB. In addition, there are two obvious percolation effect at* 15% ~ 20% *and* 30% ~ 35% *CB respectively in the course of the volume resistivity changing.*

Keywords**:** *Electrical Conductivity*, *Two Percolation Effect*, *Shielding Effectiveness*

1. Introduction

Application of plastic materials or other polymer materials on the commercial and household electron devices has been taking the place of metals gradually in terms of their advantages over metals, such as light weight, design flexibility, low costs and so on. However, when using polymer materials directly, a serious problems with electromagnetic interference (EMI) which could cause noise singles and even malfunction of the electronic appliances, is encountered due to their poor electrical conductivity [1,2]. In order to achieve the shielding effectiveness, one of the effective techniques to improve the electrical conductivity and the EMI problems is the incorporation of conductive fillers in the plastic matrix, such as carbon black, graphite, carbon fibers, metal power and so on [3]. Based on the low costs, good electrical conductivity and low density, carbon black has been utilized extensively.

As one of the five-general plastics, Acrylonitrile Butadiene Styrene (ABS) has excellent mechanical capability. The use of carbon black particles provides the polymer composite with conductivity and shielding efficiency. In the study, conductivity and shielding efficiency of nanostructural carbon black/ABS composites are analyzed.

2. Experimental

2.1. Materials

ABS (CH-510) used as matrix was provided by Panjin Ethylene Industry Co. in China. Nanostructural carbon black, which has the particles diameter of 20 ~ 30 nm, was intermediate super abrasion furnace high structure black (ISAF-HS) H234 by FuShun Dong Xin Chemical Co. Ltd. in China.

2.2. Preparation

Process under argon atmosphere, CB was preprocessed by heat treatment at 700˚C for 30 minutes in order to get rid of the oxygenous group and activate it [1,4]. ABS was dry processed for the water content less than 0.1% (mass fraction).

Then ABS and CB particles are fully blended with different compounding ratio are and pressed several times in plastic extruder（SJ25-25）at the temperature of 170˚C, 180˚C and 175˚C in feed section, melting zone and die head. At last this fully blended composites is hot pressed to be the sample with diameter *Φ*115 mm and thinness 1.5 mm under 10 MPa for measuring the EMI shielding effectiveness and volume resistivity.

2.3. Measuring Method

Three-electrode method [5] is used to measure volume resistivity, which is showed in **Figure 1**. The ration of voltage which between the high voltage electrode and guard electrode and electric current which through high voltage electrode and measure electrode was defined as volume resistance (R_V). According to this model, volume resistivity ρ_V is given as

$$\rho_V = R_V \cdot S/d$$

Here, S is measure electrode area, and d is sample thickness.

The SE of the sample for plane-wave condition/simulation was measured using the coaxial cable method .The set-up (as shown in **Figure 2**) consisted of a DN15115 SE tester, which was connected to a Hewlett-Packard(HP) 8753D vector network analyzer. An HP 8753D type N calibration kit was used to calibrate the system. Then standard attenuators with a total attenuation 100 decibels (dB) were tested to ensure that the dynamic measurement rang up to 100 dB are valid for all sample measurements. The frequency is scanned from 3 to 1.5 GHz and 201 date points are taken in reflection and also in transmission. The attenuation under transmission and that under reflection were measured. The former is equivalent to the SE.

3. Results and Discussion

3.1. Analysis on Nano-Structure CB

The study [4,6] showed that the character of CB is one of the main factor to affect the conductivity of composite. The smaller the CB size, the more complex the structure, the larger the CB specific surface area, the less surface active group and the stronger the polarity, the better the electrical conductivity of composite. CB N234 has more excellent specific surface area and fabric. The method of CTAB absorbing shows the specific surface area is 120 ~ 125 m^2/g and DBP absorbing shows the fabric is 120 ~ 125 ml/100g[6]. **Figure 3** shows the TEM micrograph of the nanometer carbon black. CB particles present globosity and the diameter is between 20 mm and 30 mm approximately. **Figure 3** shows that nanostructural CB presents the state of fusion and aggregates, which can be measured by DBP absorbing. The larger the DBP value, the larger the void volume of nanostructural particles aggregates, the more complex the structure and the better the electrical conductivity.

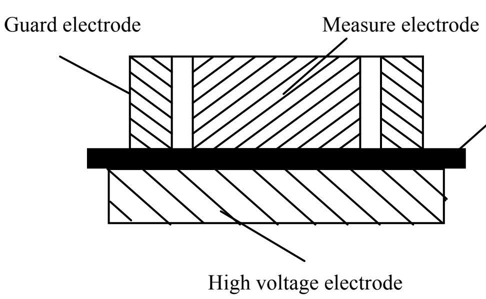

Figure 1. Three electrodes test system.

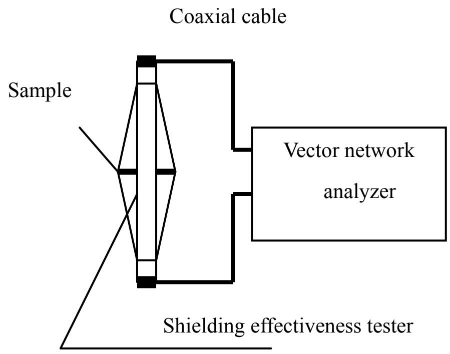

Figure 2. Set-up for EMI shielding effectiveness measurement.

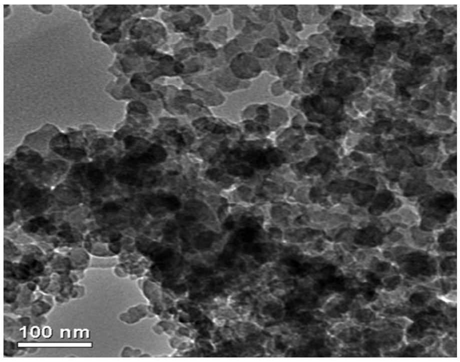

Figure 3. TEM micrograph of the nanometer carbon black.

3.2. Electrical conductivity

Different mass fractions of CB from 10% to 40% respectively were blended with ABS by hot extrusion. **Figure 4**

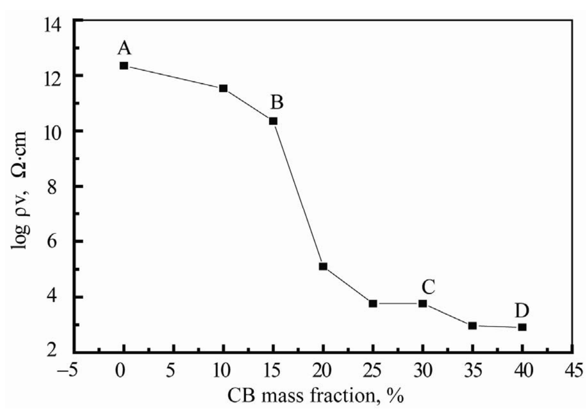

Figure 4. Effect of the nanometer carbon black content on volume resistivity.

shows the change of volume resistivity of composites with different CB loading. From the chart, it could be seen that volume resistivity doesn't decrease linear with the increase of CB fraction.

3.2.1. The Theory Analysis on Conductivity Percolation Effect

Taking the electric conduction fillers as electric conduction lattice point, the insulation layer is equivalent to potential barrier, the electric current density in multilayer materials under low voltage could be described as following [7]:

$$J = J_L \bar{\varphi}^{1/2} V e^{-A\bar{\phi}^{1/2}} \frac{1 - e^{-nA\bar{\phi}^{1/2}}}{1 - e^{-A\bar{\phi}^{1/2}}} \quad (1)$$

where, $J_L = \frac{(\alpha m)^{1/2}}{\Delta S}\left(\frac{e}{n}\right)^2$, $A = \frac{4\pi\beta\Delta s}{h}\sqrt{2m}$, and $\bar{\varphi}$ is the average potential barrier, V is external-voltage, T is temperature, ΔS is potential barrier breadth (thickness polymer parietal layer) and is given as $\Delta S = S_2 - S_1$, β is parameter, *m* is electron mass, *e* is electricity quantity of electron, h is Planck constant and n is the number of potential barrier. When conductive particles reached a value, the electrical conductivity of composites increased sharply, this should be the result of phase change. Simply, $n = 1$, Equation (1) can be written as

$$J = C/\Delta S\, exp(-D\Delta S) \quad (2)$$

It is well-known relation: $\sigma \propto J$ then,

$$\sigma = C'/\Delta S\, exp(-D\Delta S)$$

When the temperature were fixed, ΔS is dependent on the conductivity particles concentration (ρ) and has one-to-one correspondence with ρ. Based on Equation (2), if adjustable parameters C and D are fixed, and when ΔS reach to a value, the electrical conductivity changes sharply, namely, resistivity changes sharply, which is called percolation effect.

3.2.2. Analysis on Double Percolation Effect

As shown in **Figure 4** line BC and CD, the conduction nano-structure CB particles in the matrix have obvious double Percolation. When CB mass fraction is low than 15%, the composites is electrical insulator (≥ 10^9 Ω·m). For the low CB loading (< wt15%) of ABS, the concentration of the conducting CB particles in the matrix are relatively low and the CB particles were widely separated, there are large gap-widths between these CB particles, which are the barriers to the flow of electrons in the matrix. So it was hard to form a continuous conductive network, then, the main conductive mechanics is tunnel conduction [8-10]. Once the CB mass fraction is over the percolation concentration zone (wt15%), as the CB particles concentration increased and the gap-widths effectively and progressively reduced, the barrier to electron mobility dropped sharply. So volume resistivity decreased with exponential form, which is the first Percolation effect. In this area, the main conductive mechanics is contact conduction of CB particles. Less changing of CB mass fraction would result in volume resistivity change sharply. On further increase in CB loading surpassing wt30%, the volume resistivity reaches 10^3 Ω·m and the composites presents the double percolation obviously. Li [8] think of the composites electric conductivity restricted by two factors, the one is concentration of rich CB phase, the other one is the structural continuity of conducting phase. So the conclusion of two-phase percolation influencing the composites' conductivity is achieved.

3.3. Shielding Effectiveness

3.3.1. Theory of Electromagnetic Shielding Efficiency

Coaxial cable method is used to measure the SE of composites (as shown in **Figure 2**). The EMI shielding effectiveness is defined in terms of the ratio of the power of incoming and outing wave as [1]

$$SE_T = -20Log\left[\frac{E_i}{E_t}\right]$$

where, E_i and E_T are the power (electric field) of incoming and outing waves, respectively. When the plane wave is incident on shielding material, the phenomena such as reflection, absorption, transmission and diffraction are observed, so the EMI shielding is the sum of these three parts. The *SE* is described as:
$SE_T = SE_R + SE_A + SE_M$, where SE_R, SE_A and SE_M are shielding efficiency due to reflection loss, sorption loss and multiple reflections, respectively. The reason for reflection loss, which is dependent on μ_r/σ_r, is interaction between changed particles (free electron or cavity) and the electromagnetic fields. The larger the electrical conductivity, the smaller the magnetic, the larger is the reflection loss. The absorption loss is the result of thermal loss produced by the action between electric dipole or magnetic dipole and electromagnetic field. Electromagnetic wave multiple reflection in the shielding body results in the multiple reflection loss, which is looked as the corrected value of multiple reflection loss usually.

3.3.2. Analysis on SE of Composites

Figure 5 shows the EMI shielding effectiveness of ABS containing different content of CB. With the increasing of CB mass fraction from wt10% to wt35%, the volume resistivity of composites decrease and SE increase from 0.5 dB to 6 dB. This is because the electrical conductivity of a composite tends to increase with in-

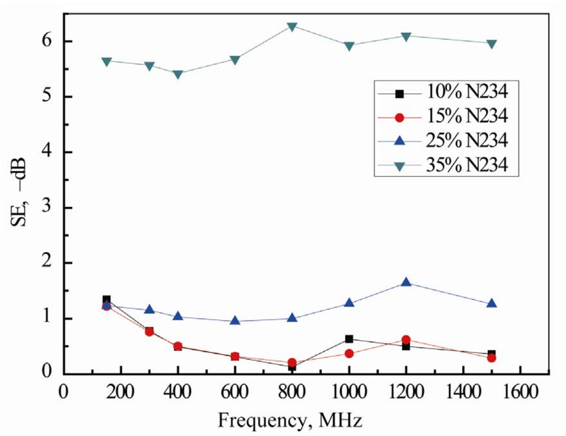

Figure 5. EMI shielding effectiveness of ABS containing different content N234.

creasing CB content, and at the action of electromagnetic radiation induction current made on the interface or in interior of the sample produces reversal electromagnetic field (Secondary radiation), which lead to increasing of surface reflection attenuation of electromagnetic wave, and consequently the EMI shielding effectiveness of the composite increases. In addition, absorbing loss and scattering loss of electromagnetic wave by ultra micro-particle contribute to SE [11].

The particle absorption cross-section σ_{ab} is written as $\sigma_{ab}=p^{ab}/p^{i}$, and particle scattering cross-section σ_{sc} can be described as $\sigma_{sc}=p^{sc}/p^{i}$, then particle extinction cross section σ_{ex} is expressed as $\sigma_{ex}=\sigma_{sc}+\sigma_{ab}$. Where, p^{ab}, p^{sc} and p^{i} are time-averaged power of absorbing wave, time-averaged power of scattering wave and time-averaged power of incident wave respectively.

It is assumed that the plane wave propagate into wave absorbing materials along X direction, and coordinate of the interface of materials and atmosphere is x = 0, and the primary electromagnetic wave energy is I_0, then the energy attenuation of the plan wave at $X = x$ is expressed as following:

$$I(x)=I_0\,exp(-n\sigma_{ex}x)$$

where, n is the number of absorbent particle in a unit volume of the composite. If the volume concentration particles and the unit volume of absorbent particle is f and v respectively, then $I(x)$ is rewrited as $I(x)=I_0\,exp(-f\sigma_{ex}x/v)$. If there are several absorbent in the composites, then $I(x)$ is expressed as $I(x)=I_0\,exp\left[-\sum n_i(\sigma_{ex})_i\,x\right]$ as well as. So increasing the absorption cross section and scattering cross section of absorbent particle can increase the attenuation of incident wave. The number of absorbent particle in a unit volume of the composite and its volume concentration increase with increasing of CB loading, so the attenuation of the incident wave energy increases. Larger specific surface area of nanostructural CB particle increase the plane wave absorption cross section and scattering cross section of absorbing particle effectively, consequently the electromagnetic wave loss is increased.

4. Conclusions

- With the increasing of CB loading, the electrical conductivity and SE of the composites increase obviously. The volume resistivity can reach 10^3 Ω·m when CB mass fraction is wt35%, and SE can increase to 6 dB.
- The volume resistivity of the composites with different CB loading presents obviously the double percolation effect, which occurred at the CB mass fraction of 15% ~ 20% and 30% ~ 35% respectively.

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