Shielding-Effectiveness Modeling of Carbon-Fiber/Nylon-6,6 Composites

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ABSTRACT: We have formulated a linear theory for the shielding effectiveness of composite matrix materials and have tested the theory for various amounts of Thermal-Graph DKD X carbon fiber within nylon 6,6. The theory predicts that the most important parameters for the shielding effectiveness of a sample are the carbon-fiber volume percentage and the frequency of the wave to be shielded. Although we expected the model to be valid at low filler-loading levels, it actually performs remarkably, covering an electrical-resistivity range of 10^{16} (at low filler-loading levels) to 10^{1} Ω cm (at high filler-loading levels), well above the percolation threshold of electrical-resistivity theory. The model performs much better than those reported in the literature and can be used to determine filler loadings needed to provide a certain level of shielding of electromagnetic waves. © 2005 Wiley Periodicals, Inc. J Appl Polym Sci 96: 62–69, 2005

Key words: fibers; modeling; nylon

INTRODUCTION

Most polymer resins are electrically insulating. Increasing the electrical conductivity of these resins allows them to be used in other applications. An electrically conductive resin can be used for static-dissipative, semiconductive (e.g., fuel gauges), and electromagnetic-interference (EMI)/radio-frequency-interference (RFI) shielding applications (e.g., computer and cellular-phone housings). The advantages of conductive resins over metals (typically used) include improved corrosion resistance, lighter weight, and the ability to adapt the shielding-effectiveness (SE) properties to suit the application needs.

Electrical-resistivity (ER; 1/electrical conductivity) values are typically 10^{14}–10^{17} Ω cm for polymers, 10^{-2} Ω cm for carbon black, 10^{-4} Ω cm for highly graphitized pitch-based carbon fibers, 10^{-5} Ω cm for high-purity synthetic graphite, and 10^{-6} Ω cm for metals such as aluminum and copper. One approach to improving the electrical conductivity of a polymer is the addition of a conductive filler material, such as carbon or metal.[1,2] Conductive resins with ERs of approximately 10^{10}–10^{3} Ω cm can be used for static-dissipative applications. Conductive resins with ERs ranging from approximately 10^{2} to 10^{1} Ω cm can be used for semiconductive applications. Those with ERs of approximately 10^{0} Ω cm or less can be used for EMI/RFI shielding applications.[3]

EMI is electrical energy that is emitted by computer circuits, radio transmitters, fluorescent lamps, electric motors, overhead power lines, lightning, and so forth. EMI/RFI can interfere with the operation of other electronic equipment nearby, causing, for example, the unwanted operation of garage-door openers, data corruption in computer systems, and pacemaker malfunction. Federal Communications Commission regulations control the amount of energy that can be emitted by an electronic product. The need for EMI/RFI materials is growing because of more stringent regulation of electronic noise and the increased need for smaller, more densely packed electronic components. A shielding material is typically used to encase an electronic product to prevent the enclosed product from emitting electromagnetic (EM) or radio-frequency energy. The shielding material either absorbs or reflects the energy within the material.[4] The SE of a material is the ratio of the power received with and without a material present for the same incident power. It is expressed in decibels:[5]

$$\mathrm{SE} = 10 \log(P_1/P_2) \quad (1)$$

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TABLE I
Properties of DuPont Zytel 101 NC010

Melting point	262°C
Glass-transition temperature	
DAM	60–70°C
50% relative humidity	~23°C
Melt flow rate	12.35 g/10 min
Shear viscosity at 1000-s^{-1} shear rate and 280°C	137 Pa s
Tensile strength at 23°C (DAM)	82.7 MPa
Flexural modulus at 23°C (DAM)	2827 MPa
Tensile elongation at break at 23°C (DAM)	60%
Notched Izod impact at 23°C	53. J/m
Density at 23°C	1.14 g/cm^3
Electrical conductivity at 23°C	10^{-15} S/cm
ER at 23 °C	10^{15} Ω cm
Thermal conductivity at 23°C	0.25 W/mK

Data taken from ref. 16.

where P_1 is the received power (W) with the material present and P_2 is the received power (W) without the material present.

An SE of 10 dB indicates that 90% of the EM energy is reflected or absorbed by the material. For EMI/RFI shielding applications, typically an SE of at least 20 dB (which indicates that 99% of the EM energy is reflected or absorbed by the material) is needed.[6]

There are many references in the literature concerning the addition of various amounts of a single conductive filler to a polymer matrix to produce an electrically conductive shielding material. For example, carbon black, carbon fibers, stainless steel fibers, and nickel-coated carbon fibers have been used.[6–10] Bushko et al.[6] showed that a conductive resin containing 24 wt % carbon fiber in polycarbonate provided an SE of 35 dB at a frequency of 100 MHz.

Several researchers have noted a relationship between the composite electrical conductivity and its SE. Materials that have higher electrical conductivity (1/ER) exhibit increased SE. In addition, increased filler orientation, length, and aspect ratio (filler length/filler diameter) can increase composite electrical conductivity and SE.[6–8,11] In the literature on composites, an equation for SE, developed by White,[4] for a planar, homogeneous, metallic barrier is often referenced. Others have conducted theoretical studies of the plane-wave shielding characteristics of composites consisting of plies of continuous, unidirectional carbon fiber/epoxy.[12–15] To our knowledge, no one has developed SE models and compared these to actual experimental results for short-fiber composites.

In this work, we performed compounding runs followed by injection molding and SE testing of short-carbon-fiber/nylon-6,6 resins. The goal of this project was to develop an SE model for these composites based on the first principles.

TABLE II
Properties of BP/Amoco ThermalGraph DKD X

Tensile strength	>1.39 GPa
Tensile modulus	687–927 GPa
ER	2.2 μΩm
Thermal conductivity (fiber direction)	400–700 W/mK
Fiber density	2.15–2.25 g/cm^3
Bulk density	0.25–0.55 g/cm^3
Fiber diameter	10 μm
Filament shape	Round
Average filament length	200 μm
Filament length distribution	<20% less than 100 μm <20% greater than 300 μm
Carbon assay	≥99 wt %
Surface area	0.4 m^2/g

Data taken from ref. 17.

EXPERIMENTAL

Materials

The matrix was DuPont Zytel 101 NC010 (Wilmington, DE), an unmodified semicrystalline nylon-6,6 polymer. The properties of this polymer are shown in Table I.[16] A BP/Amoco pitch-based milled (200-μm-long) carbon fiber, ThermalGraph DKD X, was used (Alpharetta, GA). The properties of this carbon fiber are shown in Table II.[17]

SE was measured on composites containing various amounts of carbon fiber in nylon 6,6. The concentrations (shown as weight percentages and corresponding volume percentages) and scaling factors (defined later in this article) for these single filler composites are shown in Table III.

Test specimen fabrication

For this entire project, the fibers were used as received. Zytel 101 NC010 was dried in an indirectly heated dehumidifying drying oven and then stored in moisture-barrier bags.

The extruder was an American Leistritz Extruder Corp. model ZSE 27 (Somerville, NJ). This extruder had a 27-mm corotating and intermeshing twin screw with 10 zones and a length/diameter ratio of 40. The

TABLE III
Single-Filler Loading Levels and Scaling Factors for ThermalGraph DKD X in Nylon 6,6

Carbon fiber wt %	vol %	N (dB)
5.0	2.7	8.6×10^2
10.0	5.6	1.3×10^3
15.0	8.6	3.3×10^3
20.0	11.7	5.7×10^3
30.0	18.5	1.2×10^4
40.0	26.1	2.0×10^4

screw design was chosen to obtain the maximum possible conductivity and is described in detail elsewhere.[18] Hence, a minimum amount of fiber degradation was desired along with a good dispersion of the fibers in the polymer. The Zytel polymer pellets were introduced to zone 1. A side stuffer was located at zone 7 and was used to introduce the carbon fiber into the polymer melt. Two Schenck AccuRate gravimetric feeders (Whitewater, WI) were used to accurately control the amount of each material added to the extruder.

After passing through the extruder, the polymer strands (3 mm in diameter) entered a water bath and then a pelletizer that produced nominally 3-mm-long pellets. After compounding, the pelletized composite resin was dried again and then stored in moisture-barrier bags before the injection molding.

A Niigata NE85UA$_4$ injection-molding machine (Niigata, Japan) was used to produce test specimens. This machine had a single 40-mm-diameter screw with a length/diameter ratio of 18. The lengths of the feed, compression, and metering sections of the single screw were 396, 180, and 144 mm, respectively.

A single-cavity mold was used to produce 3.2-mm-thick and 13.1-cm-diameter disks (end-gated), which were the SE test specimens. The SEs of all the formulations were determined.

SE test method

The EM SE of each formulation was measured according to ASTM D 4935-89 (reapproved 1994) for planar materials with a plane-wave, far-field EM wave.[5] An Electro-Metrics SE test fixture (model EM-2107A, Johnstown, NY) was used to hold the sample. An HP 8752C network analyzer (San Jose, CA) was used as the signal generator and receiver. For each formulation, one reference sample and at least six load samples were tested over the frequency range of 300–1000 MHz. The SE for a material was the difference between the SE value of the load samples and the SE value of the reference sample. The input power was 0 dB m (1 mW), and the tests were all conducted inside a Faraday cage to minimize interference for other electronic devices in the area. The dynamic range (the difference between the maximum and minimum signals measurable by the system) of the system was 80 dB. In addition to SE, the transmitted and reflected power was measured on at least six load samples for each formulation. The nylon-6,6-based samples were all tested dry as molded (DAM).

Filler length and aspect ratio test method

To determine the length of the carbon fiber in the SE test specimens, we used solvent digestion. A 0.2-g sample cut from the SE test specimen was dissolved at 23°C with formic acid to remove nylon 6,6. The fibers were then dispersed onto a glass slide and viewed with an Olympus SZH10 optical microscope (Orangeburg, NY) with an Optronics Engineering LX-750 video camera (Goleta, CA). The images (at 60× magnification) were collected with Scion Image 1.62 software. The images were then processed with Adobe Photoshop 5.0 and Image Processing Tool Kit 3.0 (San Jose, CA). The length and aspect ratio (length/diameter) of each fiber were measured. For each formulation, 200–3000 fibers were measured.[19–21]

Filler orientation test method

To determine the orientation of the carbon fibers, we viewed a polished composite sample with an optical microscope. For each formulation, one 13 mm × 13 mm square was cut from an SE sample. This sample was mounted in epoxy so that the sample thickness (3.2 mm face) could be viewed. The sample was then polished and viewed with an Olympus BX60 reflected light microscope at a magnification of 200×. Again, the images were collected with Scion Image 1.62 software. The images were then processed with Adobe Photoshop 5.0 and Image Processing Tool Kit 3.0. For each formulation, the orientation was determined by the viewing of 1000–4000 fibers.[18]

ER test method

The ER value of each of the carbon-fiber/nylon-6,6 formulations was measured previously DAM at 23°C. For samples with an ER greater than 10^4 Ω cm, through-plane (also called transverse) volumetric ER testing was conducted. In this method, a constant voltage, typically 10 or 100 V, was applied to the as-molded test specimen, and the resistivity was measured according to ASTM D 257 with a Keithley 6517A electrometer/high-resistance meter and an 8009 resistivity test fixture (Cleveland, OH).[22] The volumetric in-plane (also called longitudinal) ER was measured on all samples with an ER of less than 10^4 Ω cm. These samples were tested with the four-probe technique. This technique measured resistivity by the application of a constant current (typically 5–10 mA) and the measurement of the voltage drop over the center 6 mm of the sample. A Keithley 224 programmable current source and a Keithley 182 digital-sensitive voltmeter were used. Additional test method details are described elsewhere.[23,24]

RESULTS

Filler length and aspect ratio

Table IV shows the mean length and aspect ratio (length/diameter) for the carbon-fiber/nylon-6,6 com-

TABLE IV
Carbon-Fiber Orientation and ER Results in Nylon 6,6

Formulation	Length (μm)	Aspect ratio	Through-plane orientation (°)	ER (Ω cm)
Carbon fiber				
As received	167.5	16.75	—	—
5 wt%	88.5	8.85	72.5	1.0×10^{16}
10 wt%	95.3	9.53	71.6	7.6×10^{15}
15 wt%	105.8	10.58	66.5	5.2×10^{15}
20 wt%	96.5	9.65	68.6	5.0×10^{8}
30 wt%	94.7	9.47	63.4	1.2×10^{2}
40 wt%	89.4	8.94	65.1	1.0×10^{1}

Data taken from refs. 18–21.

posites after the fibers were removed via solvent digestion. The values listed under the as-received formulation are the length and aspect ratio of the carbon fiber before extrusion and injection molding.[19–21]

The results in Table IV show that there was significant degradation of the carbon fibers after the extrusion and injection-molding steps. Before the processing, the mean length of the carbon fibers was 167.5 μm, and the aspect ratio (length/diameter) was 16.75. This compares well with the reported vendor literature value of a 200-μm mean carbon-fiber length.[17] In the 20 wt % carbon-fiber/nylon-6,6 composites, the length and aspect ratio of the carbon fiber were 97 μm and 9.7, respectively. Overall, processing reduced the carbon-fiber length and aspect ratio to approximately half of its as-received values. These length results are comparable to those reported by Bigg,[25] who showed that carbon-fiber/nylon-6,6 composites had fiber lengths of approximately 130 μm after extrusion and injection molding.

Filler orientation

As discussed previously, the filler orientation angle was measured by optical microscopy. The angle of interest in these measurements was the deviation of the filler away from the angle of SE measurement. The angles were between 0 and 90°. An angle of 0° signified that the fibers were aligned parallel to the SE measurement direction. An angle of 90° meant that the fibers were perpendicular to the SE measurement direction.

Table IV also shows the mean orientation angle for the carbon-fiber/nylon-6,6 composites. The mean orientation angles varied from 63 to 72°. Hence, the orientation angle was closer to 90°, and this indicated that the fibers were primarily oriented transversely to the SE measurement direction.

ER

Table IV also displays the mean ER values for these composites. Nylon 6,6 had a mean ER of 1×10^{16} Ω cm (the vendor literature states 10^{15} Ω cm). Table IV shows that at low fiber loadings, the ER remained similar to that of the pure polymer. Then, at a point called the electrical percolation threshold, the resistivity decreased dramatically over a very narrow range of fiber concentrations. At higher fiber concentrations, the ER began to level out again at a value many orders of magnitude lower than that of the pure polymer.[26–28] In this material system, the percolation threshold occurred with 9.0 vol % (16 wt %) carbon fiber.[29]

SE

The mean SE results for the carbon-fiber/nylon-6,6 composites as a function of frequency are shown in Figure 1 for various loading levels. Increasing the amount of carbon fiber caused SE to increase, as expected. The observation of generally increasing SE with increasing frequency was expected and has been reported elsewhere.[6] As the frequency increased, the wavelength of the EM wave decreased and became

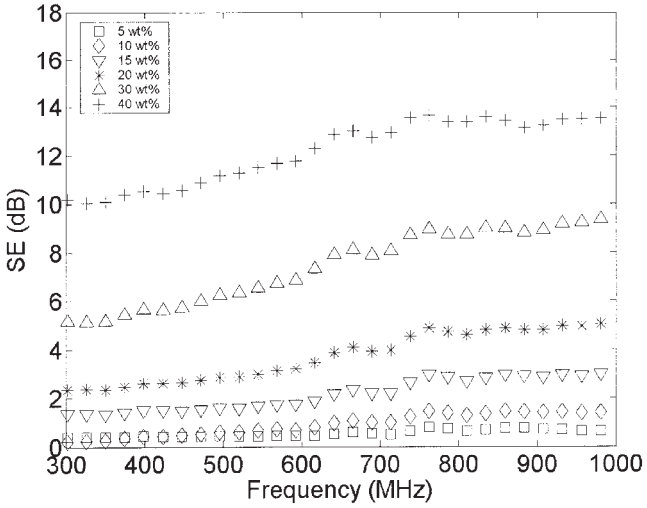

Figure 1 SE versus the frequency for carbon-fiber/nylon-6,6 composites.

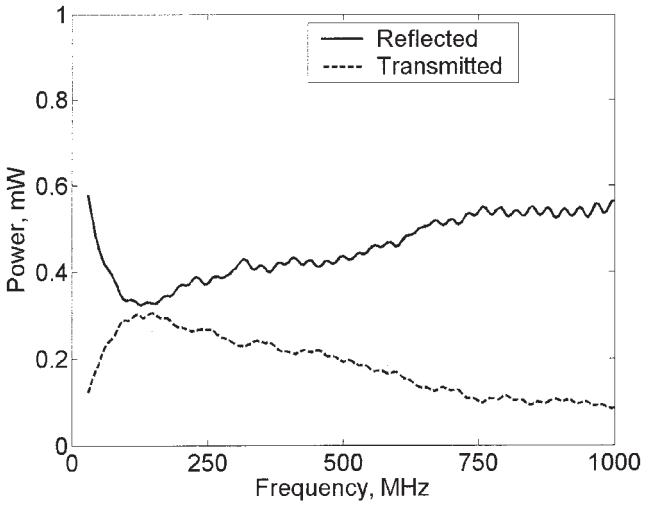

Figure 2 Reflected and transmitted power for a 30 wt % carbon-fiber sample.

closer to the size of the fiber. Thus, the higher frequency waves were more likely to encounter fiber embedded in the polymer matrix. The fibers were more likely to reflect or absorb the EM wave than the polymer-rich areas. Hence, SE increased as the frequency increased. Figure 2 shows the mean transmitted and mean reflected power versus the frequency for a composite containing 30 wt % (18.5 vol %) carbon fiber. The supplied power was 1 mW. This figure shows that at 800 MHz, the transmitted power was approximately 0.1 mW.

MODELING

As illustrated in the schematic of Figure 3, when an EM field is passed through an object of thickness t (3.2 mm in our SE samples), the incident field [of incident field strength (V/m) E_i at angle θ] forces charges in the object to oscillate at the same frequency of the incident wave. This forced oscillating charge behaves as an antenna and reradiates the incident signal. The transmitted signal exiting the object (at transmitted strength E_t) may be less than E_i because not all of the signal is reradiated in the same direction of the incident wave. The field is emitted in a pattern associated with a single-charge oscillating dipole antenna, so that the field is reflected or scattered [with reflected or scattered field strength (V/m) E_r]. Furthermore, as the charge is forced to vibrate in the medium, energy is lost in the form of heat. This mode of signal loss is known as attenuation due to absorption (of absorption strength E_a). In this project, losses were solely due to the presence of the carbon-fiber fillers as the nylon-6,6 matrix material exhibited negligible scattering or absorption losses.

It is the goal of this work to develop, from first principles, a simple model to estimate SE for composite materials. The following assumptions are used in the model:

- The direction of the impinging EM wave is perpendicular to the surface of the SE samples, so that θ is 0 in the schematic of Figure 3.
- The fibers are infinitely long cylinders with a constant radius a (5.0 μm for ThermalGraph DKD X).
- The fibers have isotropic material properties and are perfect EM conductors.
- The fibers are oriented perpendicularly to the EM wave in the TM^z mode, as illustrated in Figure 4. In this mode, the electric field vector points in the z direction and exhibits longitudinal motion in the x direction. The TM^z mode provides maximum SE because of electric charge oscillations in the carbon fiber (z direction in Fig. 4).[30]

Whether or not the incident wave interacts with the fiber depends on the incident wavelength (λ) and an EM property known as the scattering width (σ_{2D}), which is the apparent diameter of the fiber with respect to the incident wave. σ_{2D} can be derived with EM theory and is available in advanced electrical engineering textbooks:[30]

$$\sigma_{2D} = 2\pi\rho\frac{|E_r|^2}{|E_i|^2} \tag{2}$$

where ρ is the distance from the target to the observer (m). In radar applications, the limit $\rho \to \infty$ is usually applied as the observer is far away from the target. In this application, ρ was very small and was estimated to be $\rho = 1.0 \times 10^{-4}$ m. Although the model equations presented later show an explicit dependence on the choice of ρ, it does not have a qualitative effect on the results.

E_r has been determined to be an infinite series:

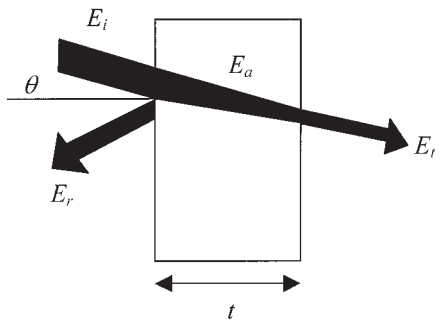

Figure 3 Representation of the plane wave contacting a cylindrical sample.

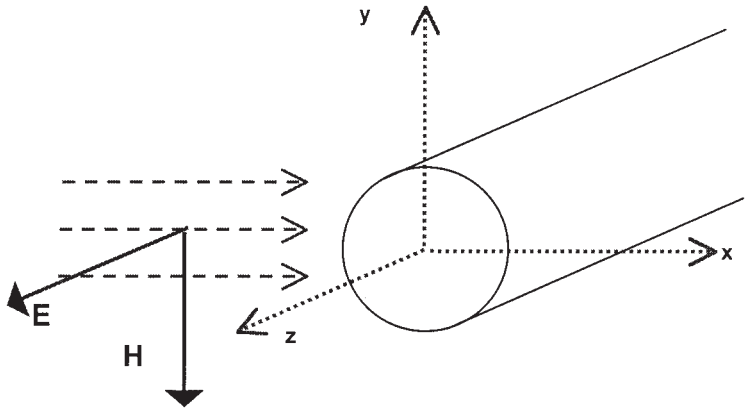

Figure 4 Depiction of the TM^z orientation for a single cylindrical scatterer (carbon fiber).

$$E_r = -E_i \sum_{n=0}^{+\infty} (-j)^n \varepsilon_n \frac{J_n(\beta a)}{H_n^{(2)}(\beta a)} H_n^{(2)}(\beta\rho) \cos[n(\theta+\pi)] \tag{3}$$

where ε_n is equal to 1 when n is 0 and otherwise is 2, j is $\sqrt{-1}$, β is the wave number ($\beta = 2\pi/\lambda$), and $\theta + \pi$ is the phase of the scattered field (rad). J_n is the Bessel function of the first kind of order n, and $H_n^{(2)}$ is a Hankel function ($H_n^{(2)} = J_n - jY_n$, where Y_n is the Bessel function of the second kind of order n).[30]

Inserting eq. (3) into eq. (2) and calculating the backscattered field (the scattered field coming back toward the incident signal) that occurs when θ is 0 rad, we obtain σ_{2D}:

$$\sigma_{2D} = 2\pi\rho \left| \sum_{n=0}^{+\infty} (j)^n \varepsilon_n \frac{J_n(\beta a)}{H_n^{(2)}(\beta a)} H_n^{(2)}(\beta\rho) \right|^2 \tag{4}$$

A sketch that depicts the three most important length scales used in determining the SE of a cylindrical fiber is shown in Figure 5. A unique and complex feature of EM waves is that although the EM wave that impinges upon the cylinder travels in the x direction (into the page in Fig. 5), it also can be considered to exhibit oscillations in the y direction with the same λ value. The likelihood of a wave being scattered by a fiber of diameter $d = 2a$ is dependent on a volumetric effect, that is, σ_{2D}/λ (also called the bistatic scattering width). The larger this ratio is, the more likely a wave will be shielded by a carbon fiber within a composite material. This premise is the basis of our new model proposed here.

On the basis of this physical argument, SE is assumed to be proportional to the bistatic scattering width:

$$\text{SE (dB)} = N\,(\text{dB}) \times \frac{\sigma_{2D}}{\lambda} \tag{5}$$

where N is the proportionality constant or scaling factor (dB). A plot of SE/(σ_{2D}/λ) as a function of frequency ω should be relatively constant and is shown in Figure 6 for samples containing 15 or 30 wt % carbon fiber. The model given by eq. (5) provides reasonable results both below and above the percolation threshold, covering an ER range (as shown in Table IV) of over 13 orders of magnitude! This is an unexpected result as a linear theory such as the one described here is expected to only be valid at low filler loadings.

The numerical value of N depends on the volume percentage of the filler and the filler material, and we obtained it here by taking the ratio of the average SE

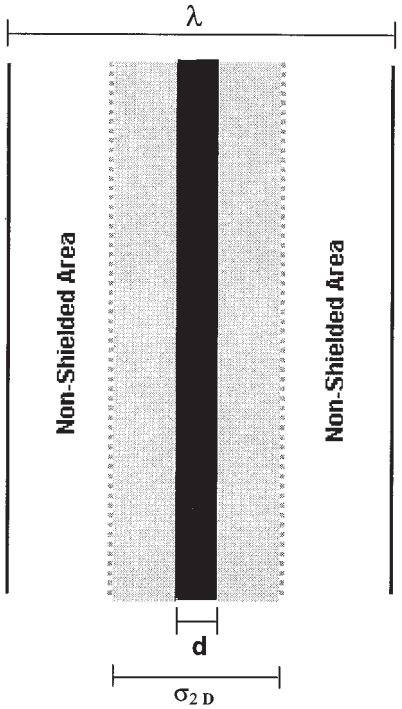

Figure 5 Pictorial description of the carbon-fiber diameter and scattering width.

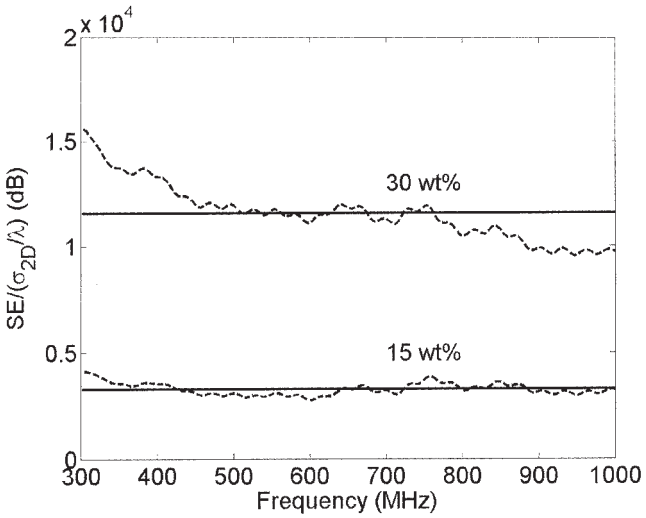

Figure 6 Scaling factor analysis for 15 and 30 wt % carbon fibers in nylon. The dashed lines are the measured data, and the solid lines are the best fits with N.

to the bistatic scattering width over the frequency range of ω_{low} = 300 MHz to ω_{high} = 1000 MHz:

$$N(\text{dB}) = \frac{\int_{\omega_l}^{\omega_h} \frac{\text{SE (dB)}}{\sigma_{2D}/\lambda}\, d\omega}{\int_{\omega_l}^{\omega_h} d\omega} \quad (6)$$

Table III lists the values for N at different filler loadings.

Further confirmation of the SE model proposed here can be obtained by the measurement of the fit quality (Q) of the model to the data:

$$Q = \frac{\text{SE (dB)}}{N(\text{dB}) \times (\sigma_{2D}/\lambda)} \quad (7)$$

It should be equal to unity for a good model. Figure 7 shows Q for all of the SE data obtained in this work, covering a filler weight percentage range of 5–40%. Additionally, a plot of SE as a function of frequency for 15 and 30 wt % carbon fiber in nylon in Figure 8 is linear, as predicted by eq. (5).

By performing a least-square analysis, we developed an empirical model to predict the value of N (dB) as a function of the volume percentage of the filler (V):

$$N(\text{dB}) = 8.5 \times 10^2\ (\text{dB/vol \%})\ V\ (\text{vol \%}) - 3.2 \times 10^3\ (\text{dB}) \quad (8)$$

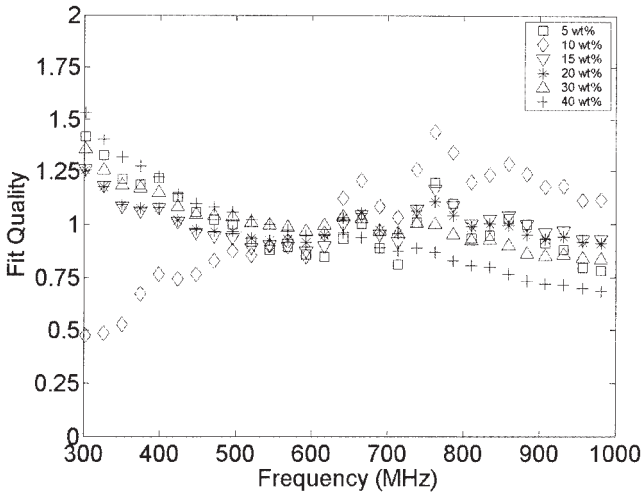

Figure 7 Model Q analysis.

The curve fit is shown in Figure 9 and has an R^2 value of 0.97. Thus, a final equation to predict SE of a composite sample can be written as follows:

$$\text{SE (dB)} = [8.5 \times 10^2\ (\text{dB/vol \%})\ V\ (\text{vol \%}) - 3.2 \times 10^3(\text{dB})]\frac{\sigma_{2D}}{\lambda} \quad (9)$$

The usefulness of this model can be ascertained by a comparison with the model of White,[4] which is usually used to predict the SE of a sample of thickness t (in.) to an EM wave of frequency ω (Hz):

$$\text{SE} = 3.34t\sqrt{\omega\mu_r\sigma_r} + 168 - 10\log\left(\frac{\omega\mu_r}{\sigma_r}\right) \quad (10)$$

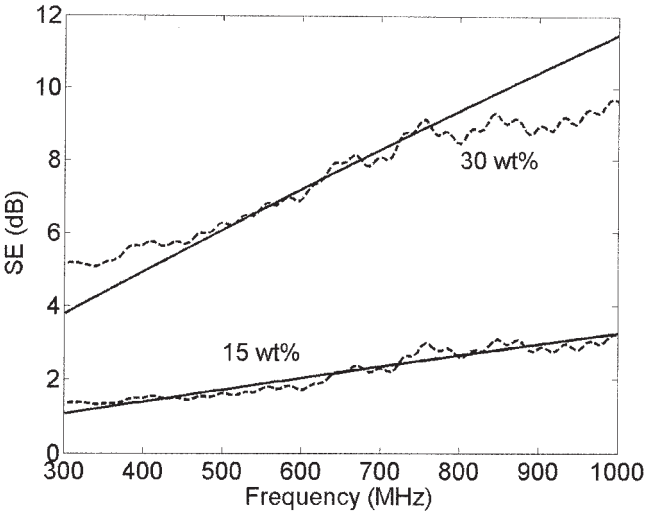

Figure 8 Model-predicted and experimentally determined SE values for 15 and 30 wt % carbon fibers in nylon. The dashed lines are the measured data, and the solid lines are the best fits with N.

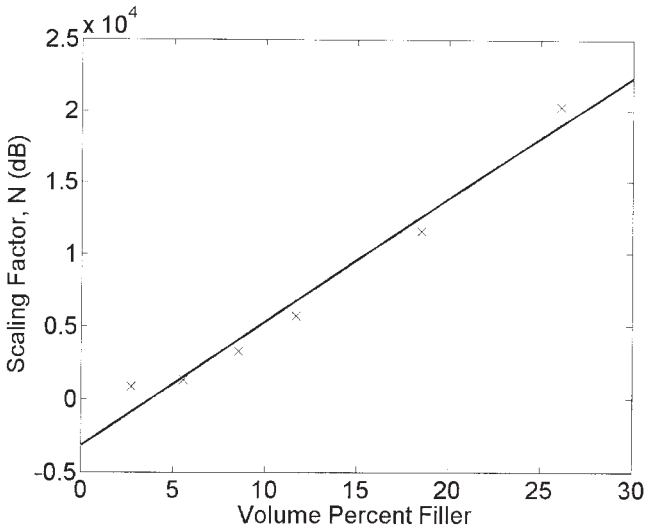

Figure 9 Linear fit for the prediction of N. The symbols are the data from Table III, and the line is a least-square fit.

where σ_r and μ_r are the conductivity and magnetic permeability, respectively, with respect to copper (the conductivity for copper is 5.82×10^5 S/cm). In this study, μ_r was 1.[6]

For composites containing 15 wt % carbon fiber, the measured SE at 300 MHz was 1.4 dB. The theory presented here [eq. (5)] predicted a value of 1.1 dB, whereas the White model [eq. (10)] predicted a value of −131 dB. At a frequency of 1000 MHz, the experimental SE of this material was 3.3 dB, which can be compared with eq. (5) (3.3 dB) and eq. (10) (−136 dB). For composites containing 30 wt % carbon fiber, the measured SE at 300 MHz was 5.1 dB; eq. (5) predicted 3.9 dB, and eq. (10) predicted 5.6 dB. At 1000 MHz, the experimental value was 9.6 dB, eq. (5) predicted 11.5 dB, and eq. (10) predicted 1.1 dB. Thus, the model presented here can predict SE with reasonable accuracy. It is expected that because the White model was developed for shielding by metals, it is valid only for homogeneous and highly conducting materials. Even for ThermalGraph DKD X filler loadings of 40 wt %, this is not the case. The validity of this hypothesis will be tested in the future for different filler materials.

CONCLUSIONS

The goal of this study was to develop an improved model for SE of composite matrix materials from first principles. It was proposed that SE was proportional to the ratio of σ_{2D} (the apparent size of the object with respect to the wave) to λ. It was also proposed that SE was proportional to the volume percentage of the carbon fiber placed within the matrix. In general, the results of the model showed agreement over a frequency range of 300–1000 MHz and an ER range of 10^{16} (at low filler-loading levels) to 10^1 Ω cm (at high filler-loading levels). This was a remarkable result as the model appears to be relatively accurate above and below the percolation threshold. This model can be used to estimate the amount of a filler needed to provide a particular SE.

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