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Electrical, morphological and rheological properties of carbon nanotube composites with polyethylene and poly(phenylene sulfide) by melt mixing

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ABSTRACT

Electrical, morphological and rheological properties of polyethylene (PE)/multi-walled carbon nanotube (MWCNT) and poly(phenylene sulfide) (PPS)/MWCNT composites were studied with the MWCNT content using vector network analyzer, scanning electron microscopy and rotational rheometry. From the results of electrical conductivity and electromagnetic interference shielding efficiency (EMI SE) of the PE/MWCNT and PPS/MWCNT composites, the electrical percolation threshold of the composites has found to be 5 and 3 wt% MWCNT, respectively. From the results of the EMI SE of the composites, it was suggested that the increase in homogeneous dispersion of the MWCNT in the PPS matrix has been attributed to the increase in connectivity of the MWCNT–MWCNT network structure of the composite. Therefore, the higher values of the EMI SE with the MWCNT content were observed in the PPS/MWCNT than the PE/MWCNT composites. From the results of the rheological properties of the PE/MWCNT and PPS/MWCNT composites, the increase in the complex viscosity was observed for the PPS/MWCNT than the PE/MWCNT composites. The increase in complex viscosity maybe due to the increase in homogeneous dispersion of the MWCNT in the PPS matrix than that in the PE matrix. From the results of the rheological properties of the PE/MWCNT and PPS/MWCNT composites, it was suggested that the homogeneous dispersion of the MWCNT in the polymer matrix has affected the increase in complex viscosity of the PPS/MWCNT composite. This result of rheological behavior is consistent with the results of the EMI SE of the PE/MWCNT and PPS/MWCNT composites.

1. Introduction

Composites of carbon nanotubes (CNTs) with polymer matrix have received considerable attention in research and industrial communities due to their good electrical conductivity, high electromagnetic interference shielding efficiency (EMI SE), high stiffness, and high strength at relatively low CNT content (Chung, 2001; Pötschke et al., 2003a; Du et al., 2004; Kim et al., 2005a; Eitan et al., 2006; Huang et al., 2007; Li et al., 2006; Pötschke et al., 2007; Lee et al., 2007; Wu et al., 2007; Jin et al., 2008).

A key issue in producing polymer/CNT composite is how to achieve a homogeneous dispersion of CNT in the polymer matrix. However, homogeneous dispersion of CNT is difficult due to the intermolecular van der Waals interactions between the CNTs, thus resulting in the formation of aggregates. This problem presents a major challenge irrespective of the method of composite preparation. Currently, three methods for homogeneous dispersion of CNTs are commonly used to introduce polymer/CNT composites, such as melt mixing (Pötschke et al., 2002; McNally et al., 2005; Zhang et al., 2006; Dai et al., 2006; Liu et al., 2007; Chen et al., 2007; Zhao et al., 2006), *in situ* polymerization (Wu et al., 2007; Tedim et al., 2008), and solution mixing (Prakash, 2001; Zhao and Gao, 2003; Yang and Gupta, 2005; Sung et al., 2006). In most of the cases, melt mixing is the preferred method of composite preparation, since aggregate formation can be minimized by appropriate application of shear during melt mixing (Pötschke et al., 2003b; Theodorou, 2007). Melt mixing for the polymer/CNT composites is more convenient than the others, and can attain the production on a large scale in the polymer industries.

Recently, a market for high filler loaded engineering plastics containing about 50% by weight of filler shows a tendency to increase; therefore, the development of high filler loaded polymer composites has been brought into the spotlight. In the studies of high filler loaded polymer composites (Payne and Whittaker, 1971), it has been found that rod-like aggregates of roughly spherical carbon black

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particles increased the material crack. However, unlike conventional carbon filler-reinforced composites, polymer/CNT composites, even low content of CNT, show good interaction between CNT and polymers (Zhou et al., 2004); therefore, smooth surfaces of the polymer/CNT composites can be achieved.

Electrical, rheological and morphological properties of polymer/CNT composites are strongly dependent on CNT dispersion in the polymer matrix. The polymer matrix is commonly electrically insulating and does not contribute to EMI shielding, although it can affect the connectivity of the conductive fillers, and connectivity may enhance the EMI shielding effectiveness. Polymer–matrix composites containing CNTs are attractive as EMI shielding materials due to reduce or eliminate beams in the electrical housing (Joo and Lee, 2000; Kim et al., 2005b; Huang et al., 2007; Liu et al., 2007).

Many reserchers (Pötschke et al., 2003a; Kim et al., 2005b; Du et al., 2004; Lee et al., 2007) reported the degree of CNT dispersion in the polymer matrix at, below and above the electrical or rheological percolation threshold. The rheological properties of polymer/CNT composites according to polymer–CNT interactions have also been reported (Lee et al., 2007). Also, the alignment and dispersion of CNTs in the polymer matrix have a strong influence on the rheological and electrical behavior of polymer/CNT composites (Eitan et al., 2006; Wu et al., 2007).

In this study, we investigate electrical and rheological properties of polymer/multi-walled carbon nanotube (MWCNT) composites produced by melt mixing. The polymers used were polyethylene (PE) and poly(phenylene sulfide) (PPS) as a matrix. The electrical properties such as electrical conductivity and EMI SE of the PE/MWCNT and PPS/MWCNT composites are reported from the measurements using four-probe method and vector network analyzer, respectively. In addition, rheological properties and morphology of PE/MWCNT and PPS/MWCNT composites are reported from the measurements using scanning electron microscopy and advanced rheometric expansion system, respectively. Electrical and rheological percolation threshold of the polymer/CNT composites obtained from the measurements of electrical conductivity and storage modulus will be discussed.

2. Experimental

2.1. Materials

PE and PPS were supplied by LG Chemical Ltd. with the commercial designation of HDPE PM 360 and PPS, respectively. The characteristics of the polymers used in this study are summarized in Table 1. MWCNT was supplied by Jeio Ltd., and the MWCNT was synthesized by the chemical vapor-grown method. Typical diameter of the MWCNT ranged from 9 to 12 nm with a length between 10 and 15 μm. The characteristics of the MWCNT are also summarized in Table 1.

2.2. Polymer/MWCNT composite preparations

Polymer/MWCNT composites were prepared by melt mixing using twin screw extruder with a screw diameter of 11 mm and a screw ratio of 40:1 length to diameter (Hankook E. M. Ltd.). For PE/MWCNT and PPS/MWCNT composites, MWCNT was ranged from 1 to 30 wt%. For PPS/MWCNT composite, temperatures of the extruder were set at 230 and 280 °C in feeding and barrel zones, respectively. For PPS/MWCNT composites, temperatures of the extruder were set at 250 and 280 °C in feeding and barrel zone, respectively. As a processing aid in the PPS/MWCNT composites, we did not use any additives such as wax or oil. Before extrusion, all the samples were dried under vacuum (< 1 mmHg) at 100 °C for 24 h.

Table 1
Characteristics of polymer and multi-walled carbon nanotube used in this study.

Sample	$\overline{M_n}$	$\overline{M_w}$	T_g (°C)[a]	T_m (°C)[a]	Diameter (nm)	Length (μm)
PE[b]	18,200	290,800	−125.7	131.1	–	–
PPS[b]	21,000	48,000	90.3	280.3	–	–
MWCNT[c]	–	–	–	–	9–12	10–15

[a]Measured in our laboratory by DSC.
[b]Supplied by LG Chemical Ltd., Korea.
[c]Supplied by Jeio Ltd., Korea.

2.3. Electrical conductivity

The surface electrical conductivity was measured for the in-plane of polymer/MWCNT composites. To measure the electrical conductivity, four-probe method was used to reduce contact resistance between probe and sample surface. Four thin gold wires (0.05 mm thick and 99% gold) were attached in parallel to the samples with conducting graphite paint (Joo and Lee, 2000). Samples were connected to a power supply (Zahner mess Technik, Model: IM6ex potentiostat) and a digital multimeter (Keithley, Model: 2000 multimeter).

2.4. EMI shielding efficiency

For EMI SE measurements, PE/MWCNT and PPS/MWCNT composites were connected to an HP 8719ES vector network analyzer (VNA) with the 2-ports flanged coaxial line holder. EMI SE was measured in the far-field region for magnetic composite films with a frequency range of 0.05–1.5 GHz using the ASTM D4935-99 method (Kim et al., 2005b).

2.5. Morphology

Morphology of the polymer/MWCNT composites was obtained by field emission scanning electron microscope (model: Hitachi S-4300). The samples were fractured at the cryogenic condition and coated by Pt before scanning. The accelerating voltage was 15 kV.

2.6. Rheological property

Dynamic measurements of rheological properties were carried out using the advanced rheometric expansion system (ARES). To prepare disc sample, PE/MWCNT and PPS/MWCNT composites were compression molded using hot press at 250 and 300 °C, respectively. Frequency sweeps from 0.1 to 100 rad/s were performed under dry nitrogen conditions. For rheological measurements, polymer/MWCNT samples were tested within the linear viscoelastic strain range.

3. Results and discussion

3.1. Electrical conductivity of polymer/MWCNT composites

The electrical conductivities (σ) of PE/MWCNT and PPS/MWCNT composites with MWCNT content are shown in Fig. 1. From Fig. 1, it is shown that the electrical conductivities of the PE/MWCNT and PPS/MWCNT composites are increased with the increase in MWCNT content. For PE/MWCNT and PPS/MWCNT composites, it appears that the electrical percolation threshold from the electrical conductivity measurements is about 5 and 3 wt% MWCNT, respectively.

The electrical percolation behavior of the polymer/MWCNT composites can be explained by the power law equation (Garboczi et al., 1995), and the correlation between the electrical conductivity and power law is shown in Figs. 2 and 3 for PE/MWCNT and PPS/MWCNT

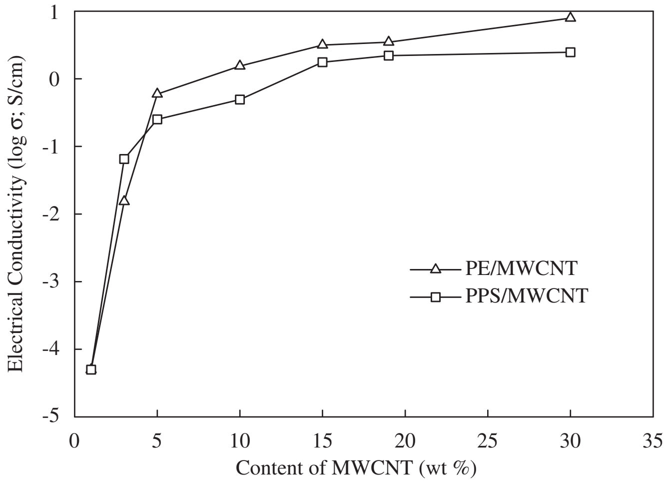


Fig. 1. Electrical conductivity of the composites with MWCNT content: (Δ) PE/MWCNT composites; (□) PPS/MWCNT composites.

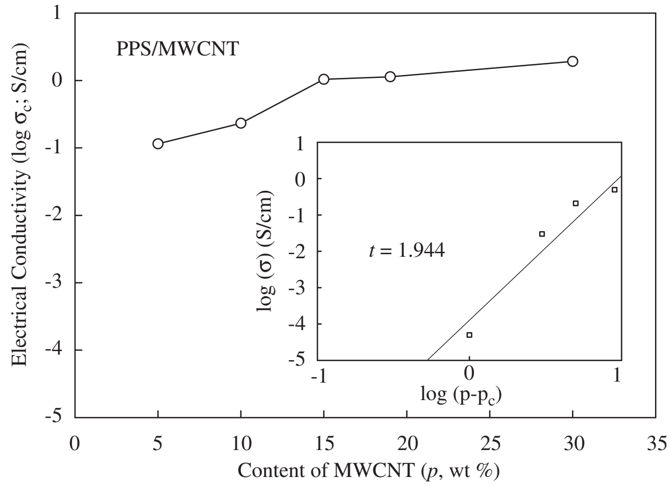


Fig. 3. Electrical conductivity of fitting curve with $p_c = 3$ using power law equation of PPS/MWCNT composite with MWCNT content. The inset shows the log–log plot of electrical conductivity (σ) vs (p–p_c) for $p > p_c$.

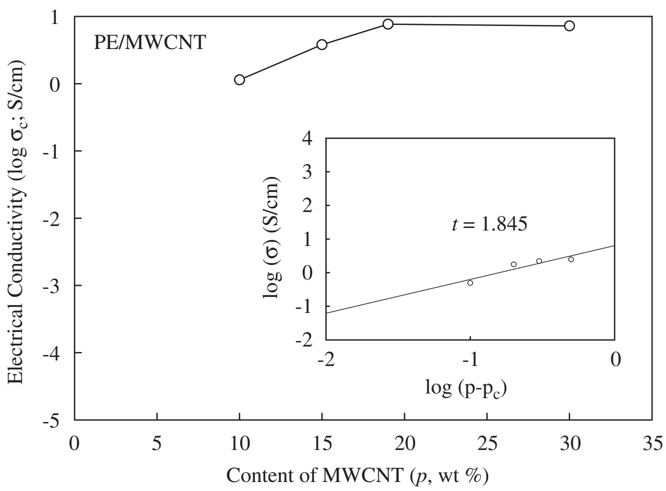


Fig. 2. Electrical conductivity of fitting curve with $p_c = 5$ using power law equation of PE/MWCNT composite with MWCNT content. The inset shows the log–log plot of electrical conductivity (σ) vs (p–p_c) for $p > p_c$.

composites, respectively. The inset in Figs. 2 and 3 shows that the electrical conductivity obeys the power law (Garboczi et al., 1995) shown in Eq. (1). At the onset of the percolative network, the electrical conductivities (σ) of composites with conductive filler concentration (p) can be described by the percolation shown in Eq. (1) as follows (Kim et al., 2005a):

$$\sigma - \sigma_0(p - p_c)^t \quad \text{for } p > p_c \tag{1}$$

where σ_0 is a fitting constant, p_c the percolation threshold, and t the critical exponent. The best results of nonlinear curve fitting are shown in Figs. 2 and 3 as the solid line for PE/MWCNT and PPS/MWCNT composites, respectively. From Fig. 2 of PE/MWCNT composites, the best-fitted constants were $\sigma_0 = 5.16\times10^{-2}$ S/cm, $t = 1.845$, and $p_c = 5$ wt%. From Fig. 3 of PPS/MWCNT composites, the best-fitted constants were $\sigma_0 = 6.51\times10^{-2}$ S/cm, $t = 1.944$, and $p_c = 3$ wt%. The exponent, t, was determined from the slope of the least-square on a log–log scale as shown in the inset of Figs. 2 and 3. From the results of Figs. 2 and 3, it is shown that the electrical percolation thresholds of 5 and 3 wt% MWCNT used in Eq. (1) for the PE/MWCNT and PPS/MWCNT composites, respectively, are in good agreement with the experimentally obtained electrical percolation thresholds shown in Fig. 1.

Many researchers (Zhang et al., 2006; McNally et al., 2005; Zhao et al., 2006) have studied electrical percolation threshold of the PE/MWCNT composites by melt mixing. Zhang et al. (2006) reported that the electrical percolation threshold of PE/single-walled carbon nanotube (SWCNT) composites with sonication and centrifuge treatment of MWCNTs was measured at 4 wt% MWCNT content and $\sigma_0 = 10^{-6}$ S/cm. McNally et al. (2005) reported that the electrical percolation threshold of PE/MWCNT composites by sprayed extruder was shown at 7.5 wt% MWCNT content and $\sigma_0 = 10^{-4}$ S/cm by volume electrical conductivity. Zhao et al. (2006) reported that the electrical percolation threshold of PE/MWCNT composites with untreated MWCNTs was observed at 15 wt% MWCNT content and $\sigma_0 = 10^{-12}$ S/cm. From the results of Fig. 2, it is suggested that the electrical percolation threshold of PE/MWCNT composites is obtained at 5 wt% MWCNT content which is somewhat lower compared that of the other researchers.

3.2. EMI shielding efficiency of polymer/MWCNT composites

Figs. 4 and 5 show EMI SE of PE/MWCNT and PPS/MWCNT composites, respectively, with MWCNT content of 1, 3, 5, 10 and 15 wt% over the frequency range of 0.05–1.5 GHz. From Figs. 4 and 5, it is shown that the EMI SE increases with the MWCNT content and ranges from 1–19 dB with the increase in MWCNT content and the values of EMI SE of PPS/MWCNT composites are observed to be higher than that of the PE/MWCNT composites. The values of experimental and estimated EMI SE of PE/MWCNT and PPS/MWCNT composites are listed in Tables 2 and 3, respectively. Tables 2 depicts that the experimental values of EMI SE of PE/MWCNT (85/15 wt%) composites at 0.5 and 1.0 GHz are found to be 14.57 and 13.32, respectively. For PPS/MWCNT (85/15 wt%) composites presented in Table 3, the experimental values of EMI SE of PPS/MWCNT composites at 0.5 and 1.0 GHz are found to be 17.80 and 17.50, respectively. The higher values of EMI SE of PPS/MWCNT composites may suggest the increase in homogeneous dispersion of the MWCNT in the PPS than in the PE matrix. The increased homogeneous dispersion of the MWCNT in the PPS matrix is related to the increased connectivity of the MWCNT–MWCNT network structure; therefore, the electrical percolation threshold was obtained at lower MWCNT content (3 wt%) in the PPS/MWCNT composite.

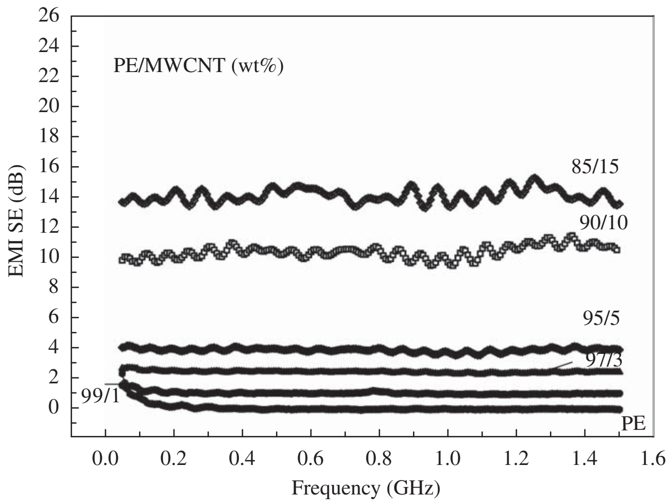


Fig. 4. Electromagnetic interference shielding efficiency (EMI SE) of PE/MWCNT composite with MWCNT content. (⊕) PE/MWCNT=100/0; (◎) 99/1; (▲) 97/3; (◈) 95/5; (◇) 90/10; (□) 85/15.

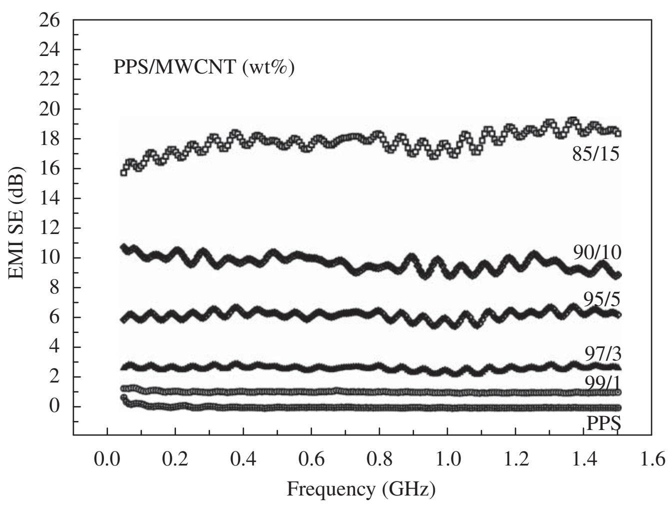


Fig. 5. Electromagnetic interference shielding efficiency (EMI SE) of PPS/MWCNT composites with MWCNT content. (⊕) PE/MWCNT=100/0; (◎) 99/1; (▲) 97/3; (◈) 95/5; (◇) 90/10; (□) 85/15.

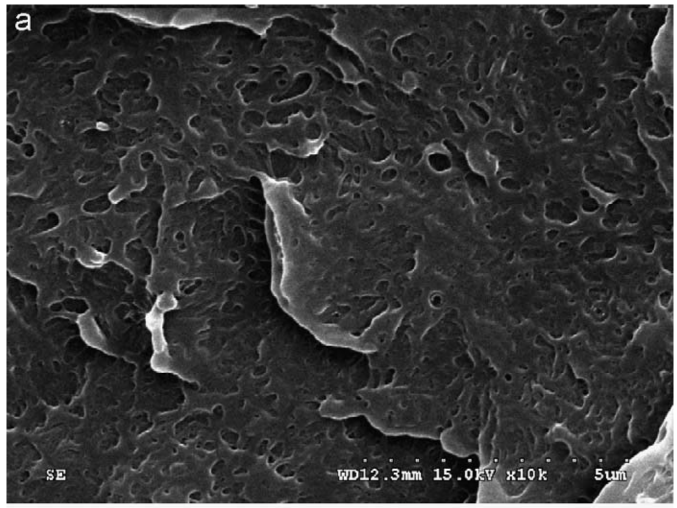
Table 2
Electrical conductivity, estimated and experimental EMI shielding efficiencies of PE/MWCNT composites with MWCNT content at 0.5 and 1.0 GHz.

MWCNT content (wt%)	Electrical conductivity (S/cm)	Estimated EMI SE (dB)	Experimental EMI SE (dB)	
			at 0.5 GHz	at 1.0 GHz
1.0	0	0	1.00	0.95
3.0	1.53×10^{-2}	5.27	2.44	2.33
5.0	5.16×10^{-2}	6.93	4.05	3.65
10.0	1.54	9.88	10.36	9.51
15.0	3.15	10.50	14.57	13.32

From the study of Joo and Lee (2000), EMI SE is defined in terms of the ratio of the power of the incident and transmitted electromagnetic (EM) wave as $SE_I \equiv 10\log(P_I/P_T) = 20\log(E_I/E_T)$, where $P_I(E_I)$ and $P_T(E_T)$ are power (electric field) of incident and transmitted EM waves, respectively. The unit of the EMI SE is decibel (dB). The EMI SE increases as electrical conductivity (σ) of shielding material increases, based on the EMI shielding theory (far-field shielding) by

Table 3
Electrical conductivity, estimated and experimental EMI shielding efficiencies of PPS/MWCNT composites with MWCNT content at 0.5 and 1.0 GHz.

MWCNT content (wt%)	Electrical conductivity (S/cm)	Estimated EMI SE (dB)	Experimental EMI SE (dB)	
			at 0.5 GHz	at 1.0 GHz
1.0	0	0	1.03	0.97
3.0	6.51×10^{-2}	5.53	3.68	3.41
5.0	2.51×10^{-1}	7.70	6.27	5.85
10.0	4.93×10^{-1}	8.91	10.25	8.79
15.0	1.76	9.64	17.80	17.50



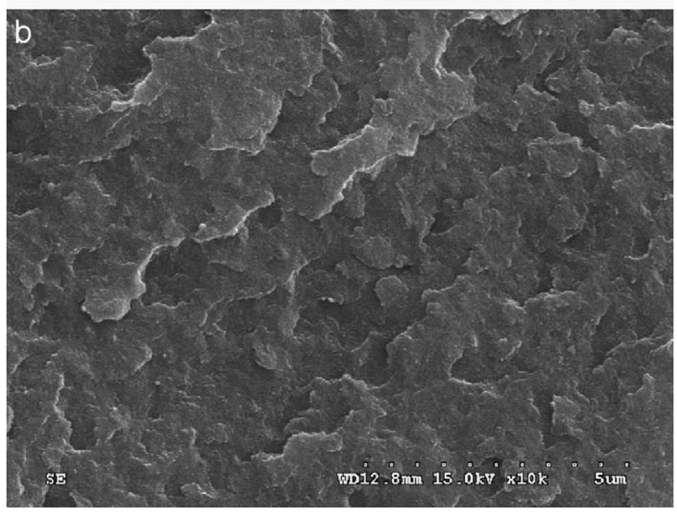


Fig. 6. Scanning electron micrographs of cryogenically fractured cross-sectional surfaces of the composites. (a) PE/MWCNT (99/1, wt%); (b) PPS/MWCNT (99/1, wt%).

eq. (2), as follows (Colaneri and Shacklette, 1992; Kim et al., 2004):

$$EMI\ SE = 20\log(1 + \tfrac{1}{2}\sigma d Z_0) \quad (2)$$

where σ is the electrical conductivity, d is the sample thickness, and Z_0 is the free space impedance (constant: 377 S^{-1}). Table 2 also reports the estimated values of EMI SE from the measurements of electrical conductivities of PE/MWCNT composites. The estimated values of EMI SE presented in Table 2 were calculated using Eq. (2).

As reported in Table 2, the experimental values of EMI SE of PE/MWCNT (95/5 wt%) at 0.5 and 1.0 GHz are found to be 4.05 and 3.65 dB, respectively, and the estimated value of EMI SE PE/MWCNT (95/5 wt%) is found to be 6.93 dB. For PPS/MWCNT (95/5 wt%)

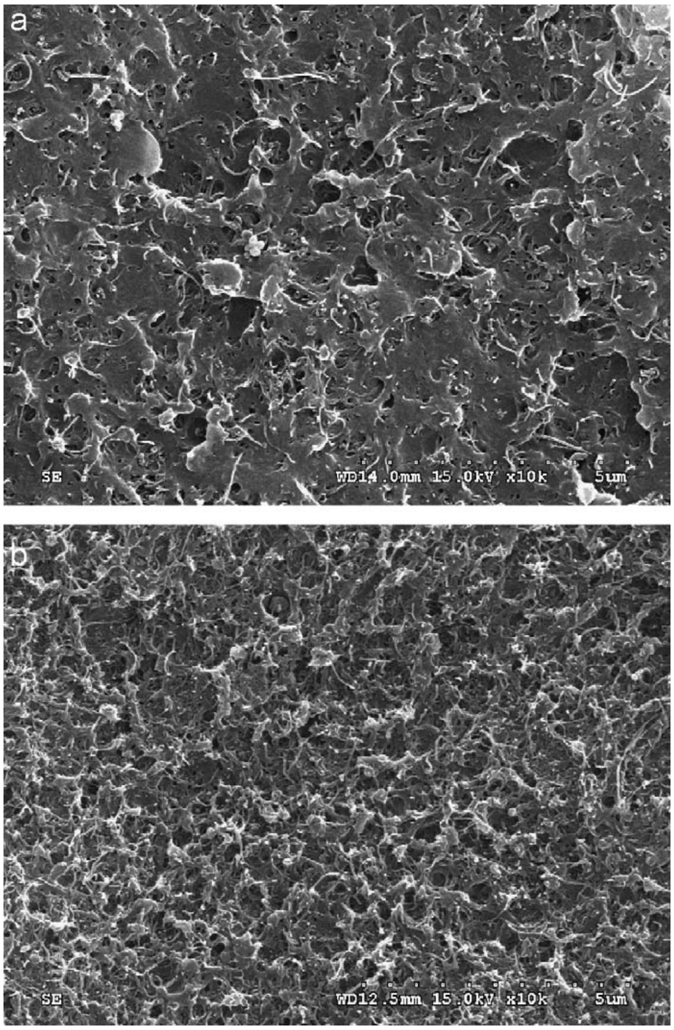


Fig. 7. Scanning electron micrographs of cryogenically fractured cross-sectional surfaces of the composites. (a) PE/MWCNT (97/3, wt%); (b) PPS/MWCNT (97/3, wt%).

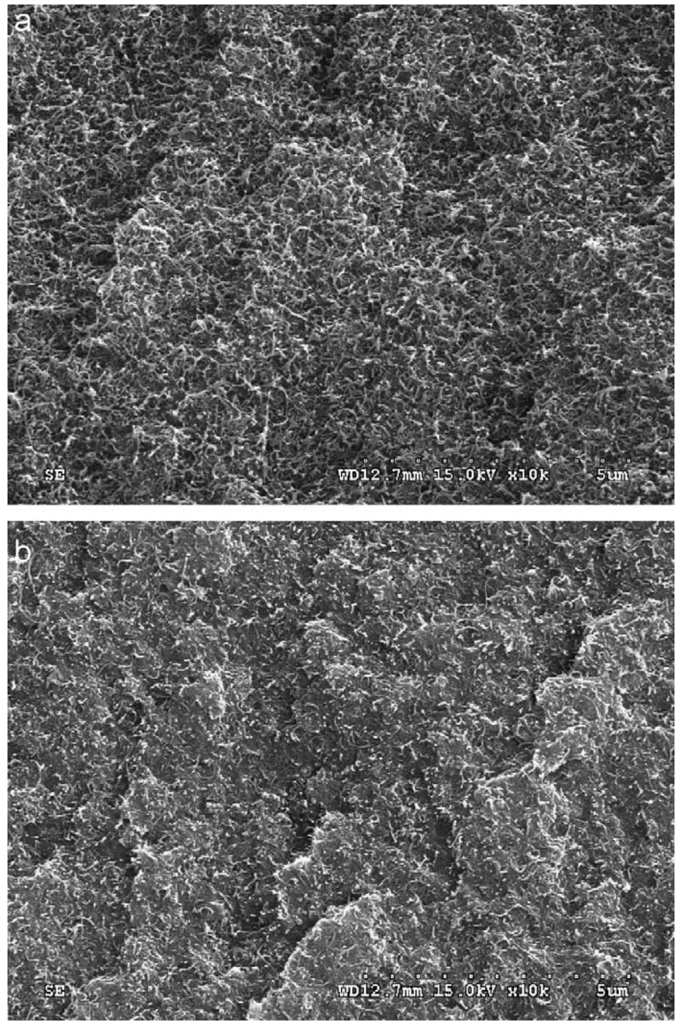


Fig. 8. Scanning electron micrographs of cryogenically fractured cross-sectional surfaces of the composites. (a) PE/MWCNT (90/10, wt%); (b) PPS/MWCNT (90/10, wt%).

presented in Table 3, the experimental values of EMI SE at 0.5 and 1.0 GHz are found to be 6.27 and 5.85 dB, respectively, and the estimated value of EMI SE PPS/MWCNT (95/5 wt%) is found to be 7.70 dB. From the results of Table 2 and 3, it is suggested that the estimated values of EMI SE of PE/MWCNT and PPS/MWCNT with the MWCNT content are in good agreement with the experimental values of EMI SE of the composites.

3.3. Morphology of polymer/MWCNT composites

Figs. 6–8 show SEM morphologies of the cryogenically fractured cross-sectional surfaces of the PE/MWCNT and PPS/MWCNT composites for the 1.0, 3.0 and 10.0 wt% MWCNT content, respectively. From Figs. 6a and b of PE/MWCNT and PPS/MWCNT composites, respectively, distribution of the MWCNT in polymer matrix is not observed clearly because of low content (1.0 wt%) of the MWCNT in the composites.

Figs. 7a and b show SEM morphologies of PE/MWCNT and PPS/MWCNT composites with 3 wt% MWCNT content, respectively. From Fig. 7, it is observed that the MWCNT seems to be distributed more evenly in the PPS matrix than in the PE matrix. This morphological behavior may have affected the electrical percolation threshold of the PPS/MWCNT which has been observed at 3 wt% MWCNT content. Figs. 8a and b show SEM morphologies of PE/MWCNT and PPS/MWCNT composites with 10 wt% MWCNT content, respectively. Figs. 8a and b show that the MWCNT is dispersed homogenously in the PE and PPS matrices, respectively. The MWCNTs are appeared to connect closely and forms a pathway between the MWCNTs. As seen in Fig. 8a and b, it is suggested that the entanglements of the MWCNTs loosen by shear during melt mixing.

From the results of the electrical conductivity and morphological behavior of the composites, it is suggested that the percolation threshold of the polymer/MWNT composites is closely related to the morphological behavior. Also, from the results of EMI SE and morphological behavior of the composites, it is suggested that the dispersion of the MWCNT in the polymer matrix is more enhanced in the PPS matrix than in the PE matrix. This increase in the homogeneous dispersion of MWCNT in the PPS matrix has affected the increase in the EMI SE of the PPS/MWCNT composite. The dispersion of the MWCNT in the polymer matrix will be discussed more in detail with respect to the rheological behavior of the composites in next session.

3.4. Rheology of polymer/MWCNT composites

Figs. 9a–c show the complex viscosity (η^*), storage modulus (G') and loss modulus (G'') of PE/MWCNT composites, respectively. From Fig. 9, it is shown that the complex viscosity, storage modulus and loss modulus of the PE/MWCNT composite increase slightly with

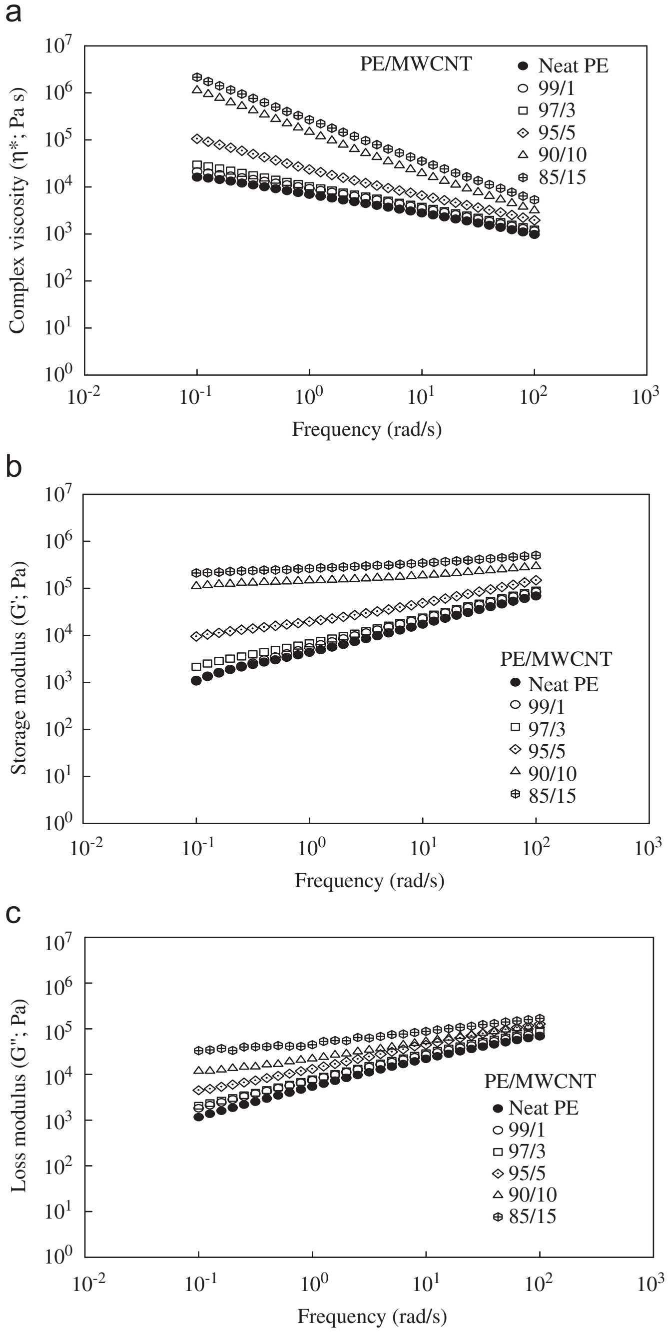


Fig. 9. Effects of weight fraction of multi-walled carbon nanotube (MWCNT) and frequency on the (a) complex viscosity, (b) storage modulus and (c) loss modulus of PE/MWCNT composite. (•) neat PE; (○) PE/MWCNT = 99/1; (□) 97/3; () 95/5; (Δ) 90/10; () 85/15.

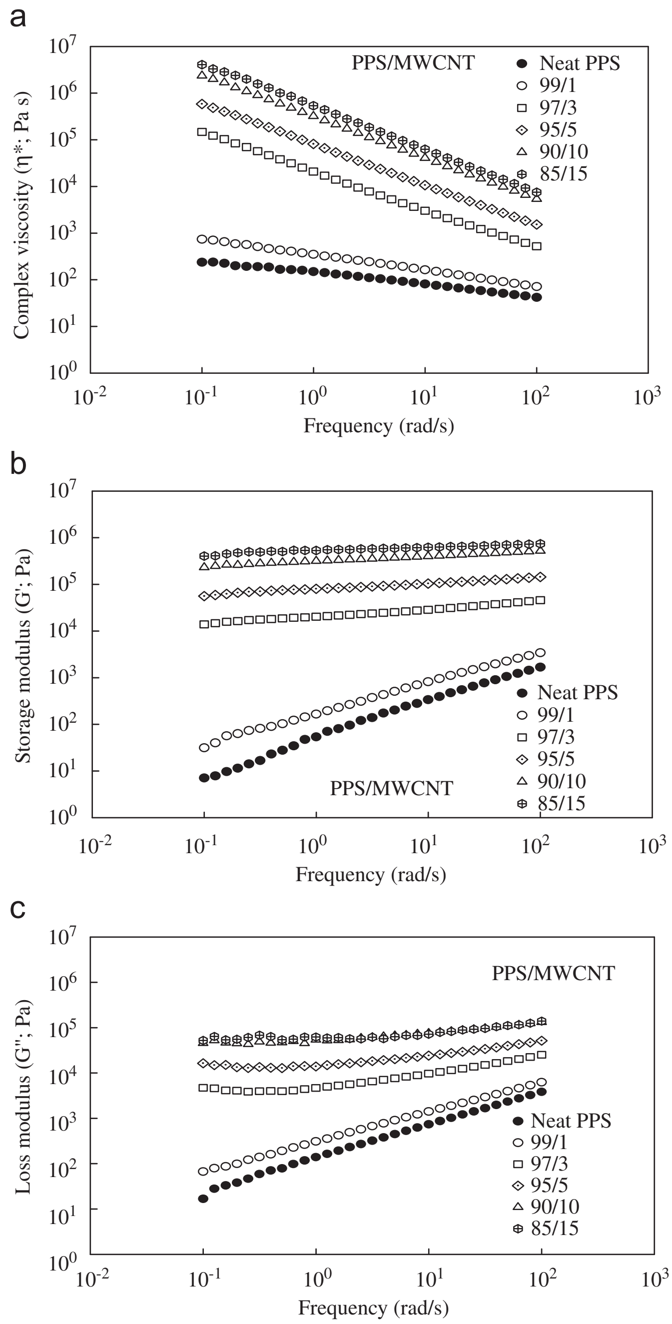


Fig. 10. Effects of weight fraction of multi-walled carbon nanotube (MWCNT) and frequency on the (a) complex viscosity, (b) storage modulus and (c) loss modulus of PPS/MWCNT composite: (•) neat PPS; (○) PPS/MWCNT = 99/1; (□) 97/3; () 95/5; (Δ) 90/10; () 85/15.

the increase in MWCNT up to 5 wt%. Then, the complex viscosity (η^*) of the composite increases appreciably at the composition of 95/5 (PE/MWCNT), which suggests that the rheological percolation threshold of the complex viscosity (η^*) is observed at about 5 wt% MWCNT content. From Fig. 9a, it is observed that the complex viscosities of the composition of 100/0, 99/1, 97/3, 95/5, 90/10 and 85/15 of the PE/MWCNT composites at the frequency of 10 rad/s are found to be 2.78×10^3, 3.50×10^3, 3.76×10^3, 6.60×10^3, 1.95×10^4 and 3.55×10^4 Pa s, respectively.

From Fig. 10a, it is observed that the complex viscosity (η^*) of the PPS/MWCNT composite increases suddenly at the composition of 97/3 (PPS/MWCNT), which suggests that the rheological percolation threshold of the complex viscosity (η^*) is observed at about 3 wt% MWCNT content. From Fig. 10a, it is observed that the complex viscosities of the composition of 100/0, 99/1, 97/3, 95/5, 90/10 and 85/15 of the PPS/MWCNT composites at the frequency of 10 rad/s are found to be 8.10×10^1, 1.63×10^2, 3.01×10^3, 1.06×10^4, 4.06×10^4 and 6.26×10^4 Pa s, respectively. From Figs. 9 and 10, it is observed that complex viscosities (η^*) of the PPS/MWCNT composites are observed to be higher than those of the PE/MWCNT composites. Similar behavior was observed for the storage and loss modulus of the PE/MWCNT and PPS/MWCNT composites which are shown in Figs. 9b and c and 10b and c, respectively.

The increase in the complex viscosity of the PPS/MWCNT composite compared to that of the PE/MWCNT maybe due to the increase in the homogeneous dispersion of the MWCNT in the PPS matrix than that of the PE matrix. The polar group of the PPS may contribute to enhance the dispersion of the MWCNT in the PPS matrix compared that of the PE matrix which shows non-polarity (Schwartz and Bahadur, 2001; Sasanuma et al., 2002). Also, the increase in the MWCNT dispersion in the PPS matrix maybe due to the lower value of the complex viscosity of the PPS (8.10×10^1 Pa s at 10 rad/s) compared to that of the PE (2.78×10^3 Pa s at 10 rad/s).

From the results of the rheological properties of the PE/MWCNT and PPS/MWCNT composites, it is suggested that the homogeneous dispersion of the MWCNT in the polymer matrix affects the increase in complex viscosity of the PPS/MWCNT composite. The results of the rheological behavior of the PPS/MWCNT composite are consistent with the results of the EMI SE of the PPS/MWCNT composite.

4. Conclusions

In this study, the electrical, morphological and rheological properties of the PE/MWCNT and PPS/MWCNT composites were investigated. From the results of electrical conductivity of the PE/MWCNT and PPS/MWCNT composites, the electrical percolation threshold of the composites has found to be 5 and 3 wt% MWCNT, respectively. The electrical percolation behavior of the polymer/MWCNT composites has been explained by the power law equation, and the correlation between the electrical conductivity and power law was in good agreement with the experimentally obtained electrical percolation thresholds.

From the results of EMI SE of the PE/MWCNT and PPS/MWCNT composites, it is understood that the EMI SE increased, in the range of 1–19 dB, with the increase in MWCNT content. The values of EMI SE of PPS/MWCNT composites showed were higher than that of the PE/MWCNT composites. From the results of the EMI SE of the composites, it was suggested that the increase in homogeneous dispersion of the MWCNT in the PPS matrix has been attributed to the increase in connectivity of the MWCNT–MWCNT network structure. Therefore, the higher values of the EMI SE were observed in the PPS/MWCNT than PE/MWCNT composites.

From the results of the rheological properties of the PE/MWCNT and PPS/MWCNT composites, the increase in the complex viscosity was observed for the PPS/MWCNT composite than the PE/MWCNT composite. The increase in complex viscosity maybe due to the increase in homogeneous dispersion of the MWCNT in the PPS matrix than that in the PE matrix. From the results of the rheological properties of the PE/MWCNT and PPS/MWCNT composites, it was suggested that the homogeneous dispersion of the MWCNT in the polymer matrix has affected the increase in complex viscosity of the PPS/MWCNT composite. The result of the rheological behavior is consistent with that of the EMI SE of the PE/MWCNT and PPS/MWCNT composites.

Notation

d	thickness
p_c	percolation threshold
p	mass fraction
t	critical exponent
Z_0	free space impedance

Greek letters

β	critical exponent
v	volume fraction
σ	electrical conductivities
σ_0	fitting constant

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