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Improving electrical conductivity of poly methyl methacrylate by utilization of carbon nanotube and CO_2 laser

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ABSTRACT: In this work, the electrical surface conductivity enhancement of injection-molded multiwalled carbon nanotube (MWCNT)/poly(methyl methacrylate) (PMMA) nanocomposite by using CO_2 laser processing was studied. Variable input factors are considered as MWCNT concentration (in three levels 0.5, 1, and 1.5 wt %), the laser feed angle with the flow direction (in five levels 0°, 30°, 45°, 75°, and 90°), and the cavity machining method that were produced by electrodischarge machining and computer numerical control milling with finishing process. The studies show that the irradiation of laser and utilization of covering gas could enhance the CNT–CNT contacts and the surface electrical conductivity. The morphology of laser-irradiated surface by using scanning electron microscope certified that the conductive network generated from CNT–CNT contacts can transfer the electrical current. The findings clearly show that the laser feed angle with the flow direction influenced the electrical conductivity. The maximum conductivity ($\sim 5.310 \times 10^{-4}$ S) was observed at 75°. © 2015 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2015**, *132*, 42671.

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INTRODUCTION

Polymeric materials filled with electrically conductive nanoparticles are currently of great interest for use in an extensive range of electronic, aerospace, and military applications, including high-strength fibers, in molecular wires, flexible electronics, electromagnetic induction shielding, electrostatic dissipation, and as biomolecule sensors. The decreasing of electrical resistivity is an important field in polymeric nanocomposite science. Small loadings of multiwalled carbon nanotube (MWCNT) can enhance the electrical conductivity of polymeric composites up to several orders of magnitudes.[1,2]

The aspect ratio is the most significant parameter of CNTs geometry that a large aspect ratio of CNTs can enhance the nanocomposite properties.[3] The CNTs have higher aspect ratio and better mechanical and electrical material properties than other reinforcements.[4,5] The first realized commercial application of CNTs in polymeric composites was for the purpose of electrical conductivity.[6] Pötschke *et al.*[1] investigated the properties of MWCNT/polycarbonate (PC) by melt mixing and found that volume electrical resistivity of PC is decreased by MWCNTs. Du *et al.*[7] stated the alignment of single-walled carbon nanotubes in poly(methyl methacrylate) (PMMA), which is an important factor of the electrical properties and the electrical conductivity of a 2 wt % composite that reduced from 10^{-4} S/cm (unaligned) to 10^{-10} S/cm (aligned). Wu and Shaw[8] measured the electrical conductivity of four different nanocomposites in the in-flow direction and perpendicular to the flow direction and reported that the nanocomposites produced by injection molding have an anisotropic electrical conductivity. In addition, this phenomenon was reported by Kimura *et al.*[9] A comparative study on the electrical behavior of MWCNT/polypropylene (PP) prepared by diluting master batches with various types of PPs showed the type and viscosity of the diluting polymer play a significant role on the dispersion of CNTs in the matrix.[10] In the case of MWCNT/polystyrene (PS), dramatic change on electrical properties was observed by increasing MWCNT loading from 0 to 2 wt %.[11] About 1 vol % of MWCNTs in ABS matrix increased the electrical conductivity to about 10^{-1} S/cm.[12] Annala[13] compared the electrical and mechanical properties of MWCNT/PS and MWCNT/PMMA nanocomposites produced by melt mixing and found that the electrical resistivity of the composites was more dependent on the method of CNT addition. In another study, the mechanical and electrical properties

Table I. Characteristics of Used MWCNTs

Characteristic	Amounts
Purity	>95%
Outside diameter	30–50 nm
Inside diameter	5–15 nm
Length	10–20 μm
SSA	90–120 m^2/g
True density	~ 2.1 g/cm^3
Aspect ratio	200–666

of MWCNT/PS and PMMA were investigated, and the results showed that the surface electrical resistivity was decreased by increasing amount of MWCNT.[14] They revealed that the decreasing of thermal conductivity of PMMA by adding carbon nanotubes is possible. In addition, the effect of injection molding parameters on the electrical resistivity was evaluated. The results exposed that the most effective parameters are the injection velocity and melt temperature, whereas holding pressure and mold temperature have only low influence.[15,16] Moreover, increasing the amount of MWCNT decreased the surface and volume resistivity of PMMA.[15] McClory *et al.* investigated the influence of the aspect ratio and produced method of CNT on rheological and electrical properties of MWCNT/PMMA. In their research, the extrusion method was used to mixing of material. The very low decreasing of volume electrical resistivity was obtained for the high aspect ratio, and the use of 1 wt % of CNT with low aspect ratio could improve the electrical conductivity.[17] The electrical conductivity level of the nanocomposites can be regulated by controlling the nanotube alignment and CNT–CNT contacts.[18–22] The processing method and the mold geometry considerably affect electrical resistivity.[16,23] Higher CNT alignment resulting from a higher shear rate led to a decrease in the electrical conductivity of the samples. The highest electrical resistivity was obtained from the microinjection-molded samples, and the lowest electrical resistivity was attributed to the compression molding.[18,23] Depending on the CNT loading, the alignment of nanotubes can decrease the probability of CNT–CNT contacts in polymers and can noticeably affect the percolation threshold, which is the critical CNT loading required to establish a conductive network, and the electrical conductivity of CNT-based nanocomposites.[23,24] The partial alignment of nanotubes can be attained by using processes such as extrusion and injection molding,[15,25] and it can decrease the electrical resistivity to a very low extent.[17] This is due to the low contact between nanotubes.

This work investigated the increasing of surface electrical conductivity of injection-molded MWCNT/PMMA nanocomposite in two different cavities by using CO_2 laser. The change of axial angle of carbon nanotubes on produced nanocomposites to enhance the surface electrical conductivity by utilization of CO_2 laser process is the primary hypothesis of this research. In addition, the cavity machining method, concentration of MWCNTs, and angle with the flow direction were considered as the variable parameters.

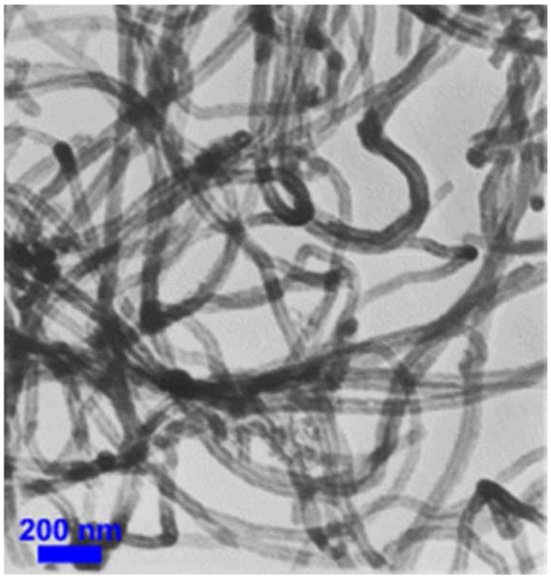

Figure 1. SEM image of the MWCNTs. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

EXPERIMENTAL

Materials

The PMMA pellets used in this study were obtained from CHI MEI Corporation (Taiwan), with the grade name of CM205. The melt flow index (MFI) of PMMA is 14 mL/10 min, and its density is 1.19 g/cm^3. The MWCNT used in this research is prepared from Nanostructured and Amorphous Materials (Texas, USA). The carbon nanotube has been produced by the chemical vapor deposition method. Table I shows the characteristics of MWCNTs. In addition, Figure 1 depicts the scanning electron microscope (SEM) image of the MWCNTs.

Production of Nanocomposite Sheets

To produce the MWCNT/PMMA pellets, the extrusion method was used, which is one of the most commercial methods for mixing of materials.[3] For this purpose, first, both PMMA and carbon nanotubes were dried at 80°C for 4 h in an oven. Then, 0.5, 1, and 1.5 wt % of MWCNTs were added to PMMA pellets, because the percolation threshold was observed in higher MWCNT concentration.[1] After physically mixing of MWCNTs and PMMA pellets, a Coperion ZSK25 corotating twin-screw extruder was used to produce PMMA/MWCNT pellets. The use of high rotation speed and low temperature enhance the dispersion of carbon nanotubes in a polymer matrix.[26,27] Table II displays the extruder parameters that were set to produce the nanocomposites. Then, the extruded blends of PMMA/MWCNT

Table II. Extruder Parameters

Parameter	Amount
Barrel zones temperatures (°C)	200–210–230–225–230–220
Rotating speed of the extruder (rpm)	250
Output pressure (rpm)	135

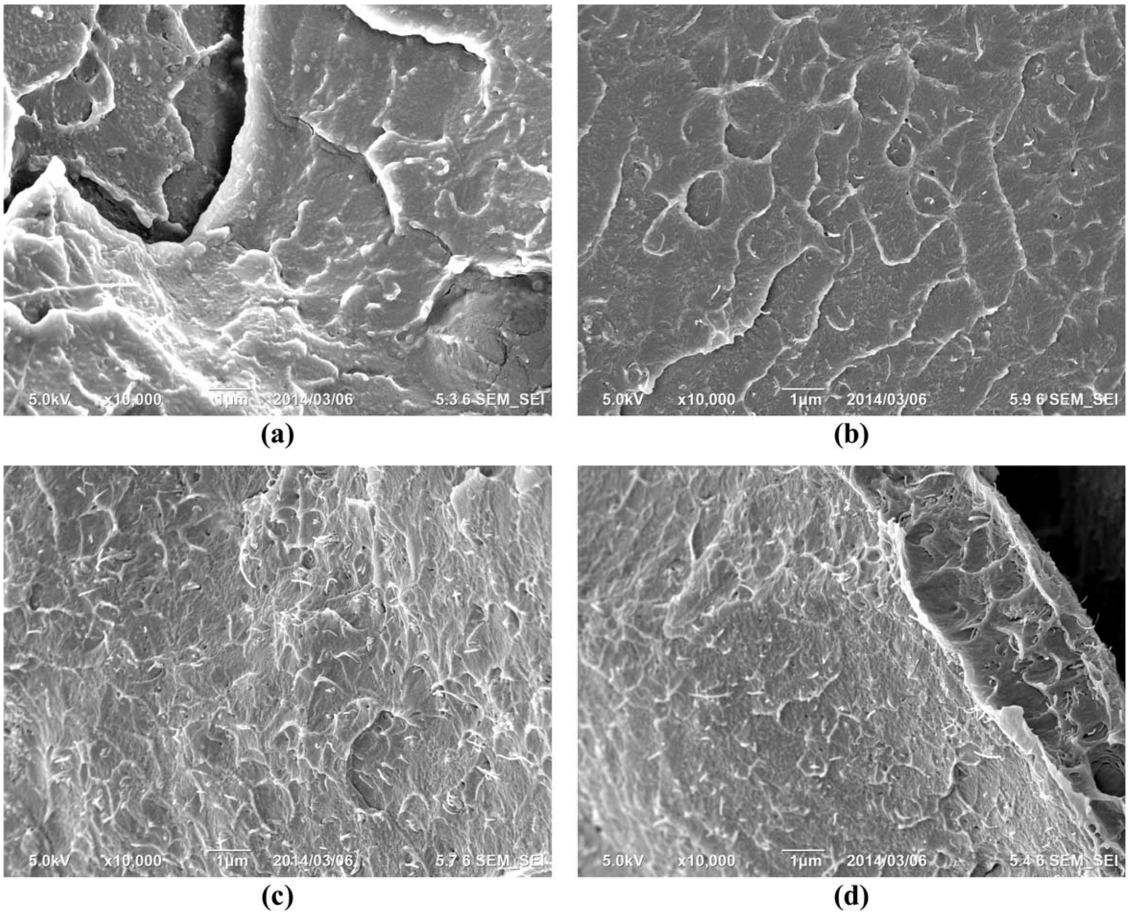

Figure 2. SEM images of the produced specimens: (a) pure PMMA; (b) PMMA with 0.5 wt % MWCNT nanocomposite; (c) PMMA with 1 wt % MWCNT; and (d) PMMA with 1.5 wt % MWCNT nanocomposite.

were cut into pellets. The PMMA/MWCNT pellets were also dried at 80°C for 24 h.

In the next stage, to produce nanocomposite sheets, a mold containing two different cavities with dimension of 175 mm × 80 mm × 3.5 mm were used, in which one of the cavities were produced by electrodischarge machining (EDM) and another by computer numerical control (CNC) milling machine with finishing process. Nanocomposite sheets were produced using a NBM HXF-128 plastic injection molding. Injection and holding pressure of the process was set at 80 and 60 bar, respectively, and the temperatures of barrel zones were set at 220, 235, 250, and 250°C. For better dispersion of nanotubes in polymer matrix, mold temperature is considered as low as possible (i.e., 28°C).[16] After producing nanocomposite samples, SEM images of their cross section were taken to certify the dispersion of nanotubes in the polymer matrix (Figure 2).

Laser Process

Laser process is carried out using a laser system consisting of 120 W continuous CO_2 laser (YM Laser Machine CM1328), with two axes CNC table with the work volume of 1300 mm × 2800 mm. The laser beam was irradiated in different angles with the flow direction.

Three parameters, MWCNT concentration (in three levels), angle with the flow direction (in five levels), and mold cavity machining type (in two methods), are considered as the variable parameters. Table III relates the variable parameters and their

Table III. Levels of the Variable Parameters of This Research

Parameters	Symbol	Levels of the input parameters of this research				
MWCNT (wt %)	M	0.5	1	1.5	–	–
Angle with flow direction (degree)	θ	0°	30°	45°	60°	90°
Mold cavity machining type	C_t	Cavity A (produced by EDM)			Cavity B (produced by CNC milling with finishing process)	

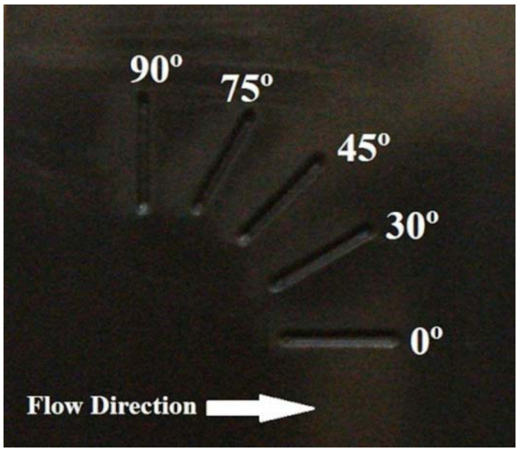

Figure 3. A specimen after laser processing.

levels. The designs of experiment were used by full factorial method, and every experiment run was replicated six times.

The compressed air was used as the covering gas with 0.28 bar pressure. The power and feed rate were considered to be 50 W and 4 m/min, respectively. The focal point is fixed at 15 mm above the work piece. The mentioned amounts can just remove a layer of material from the surface of specimens. The type of used lens was stable, and its ideal cutting width was 0.2 mm. Figure 3 depicts a specimen after laser processing.

After laser process, the SEM images show some free carbon nanotubes. To remove them and improve the accuracy of electrical tests, the ultrasonic cleaner (model SW6H, Swiss) was applied. In addition, distilled water with constant temperature about 50°C was used as a washer liquid. The frequency and ultrasonic power were set at 38 kHz and 600 W, respectively. In addition, the surface gloss of samples was measured by Gloss Master 60° (model 4328, Germany).

Electrical Resistivity Measurements

The test results show that all of the nanocomposites have a surface electrical resistivity up to 2×10^{14} Ω. The surface resistivity of the laser-irradiated samples was tested with a four-pin probe Agilent multimeter (3458A model, USA). The applied voltage to measure resistivity was 5 V. The platinum probes with special shape and fixture were designed and manufactured (Figure 4). According to ASTM D-257, the measured surface resistance, R_s, was converted to surface resistivity, ρ_s, according to the following equation:

$$\rho_s = R_s \times \frac{W}{L}, \tag{1}$$

where W is the effective width of measuring electrodes and L is the distance between two probes.

RESULTS AND DISCUSSION

Morphological Characterization

The SEM images (JEOL, Jib-4601f) of laser-irradiated samples are shown in Figures 5 and 6. According to these images, after laser beam contact with the sample surface and consequently materials melting, the blast of covering gas could bollix the dispersion and alignment of carbon nanotubes. The partial alignment of CNTs parallel with laser feed angle can be inferred from SEM images. The noticeable difference does not exist between produced samples with two different cavities. In addition, it is clear that the contact of CNTs was enhanced and the gap distance between them was reduced. The touching of nanotubes form the aggregate conductive path that it can transfer the electrical current. Furthermore, because of the reduction of nanotubes distance, the tunneling phenomenon can occur, which is a significant factor in electron transferring. It seems that the performed laser process could assist the alternation of nanotubes angle. The maximum density of conductive network was observed at $\theta = 75°$. This result demonstrates that more intersections were created when the nanotubes were aligned with 75° axial angle, illustrating that the electrical conductivity is more feasible in this condition. By increasing the laser feed angle from 75° to 90°, agglomerated MWCNT bundles were observed, which decreases the electrical conductivity.

Surface Electrical Properties

An intense increase of conductivity was observed on laser-irradiated surfaces. Therefore, to improve the surface electrical conductivity, utilization of CO_2 laser process can be useful. According to the obtained results, the surface resistivity of samples before laser processing were $\sim 2 \times 10^{14}$ Ω; however, their surface resistivity was reduced down to 1.88×10^{3} Ω by laser processing for the nanocomposite with 1.5 wt % MWCNT produced with Cavity B in 75°.

The effect of various parameters on the surface electrical resistivity and conductivity are shown in Figures 7 and 8. Figure 7(a,b) depicts the interaction effect of laser feed angles with the flow direction and MWCNT concentration on the surface electrical resistivity and the surface electrical conductivity, respectively. The effect of feed angle can be clearly concluded from these figures. The tangible alternations of electrical resistivity by increasing the angle can be seen for nanocomposites with 0.5 wt % MWCNT. According to the obtained results of this research, the minimum electrical resistivity and maximum electrical conductivity can be achieved at $\theta = 75°$.

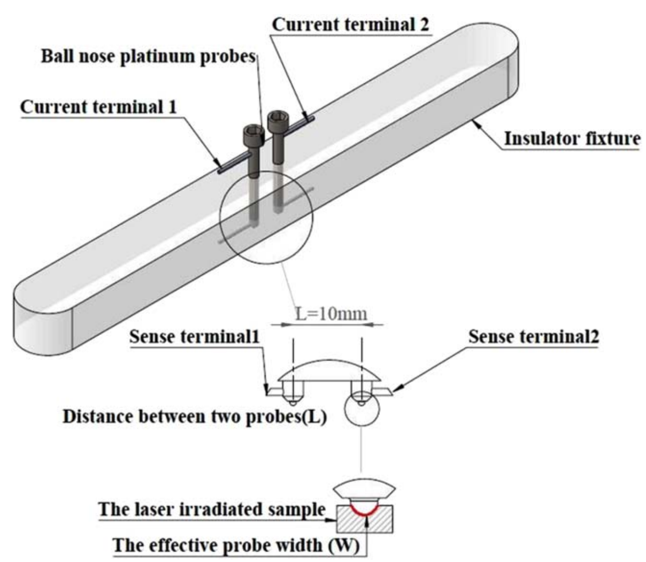

Figure 4. The schema of equipment and electrical measurement characters. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

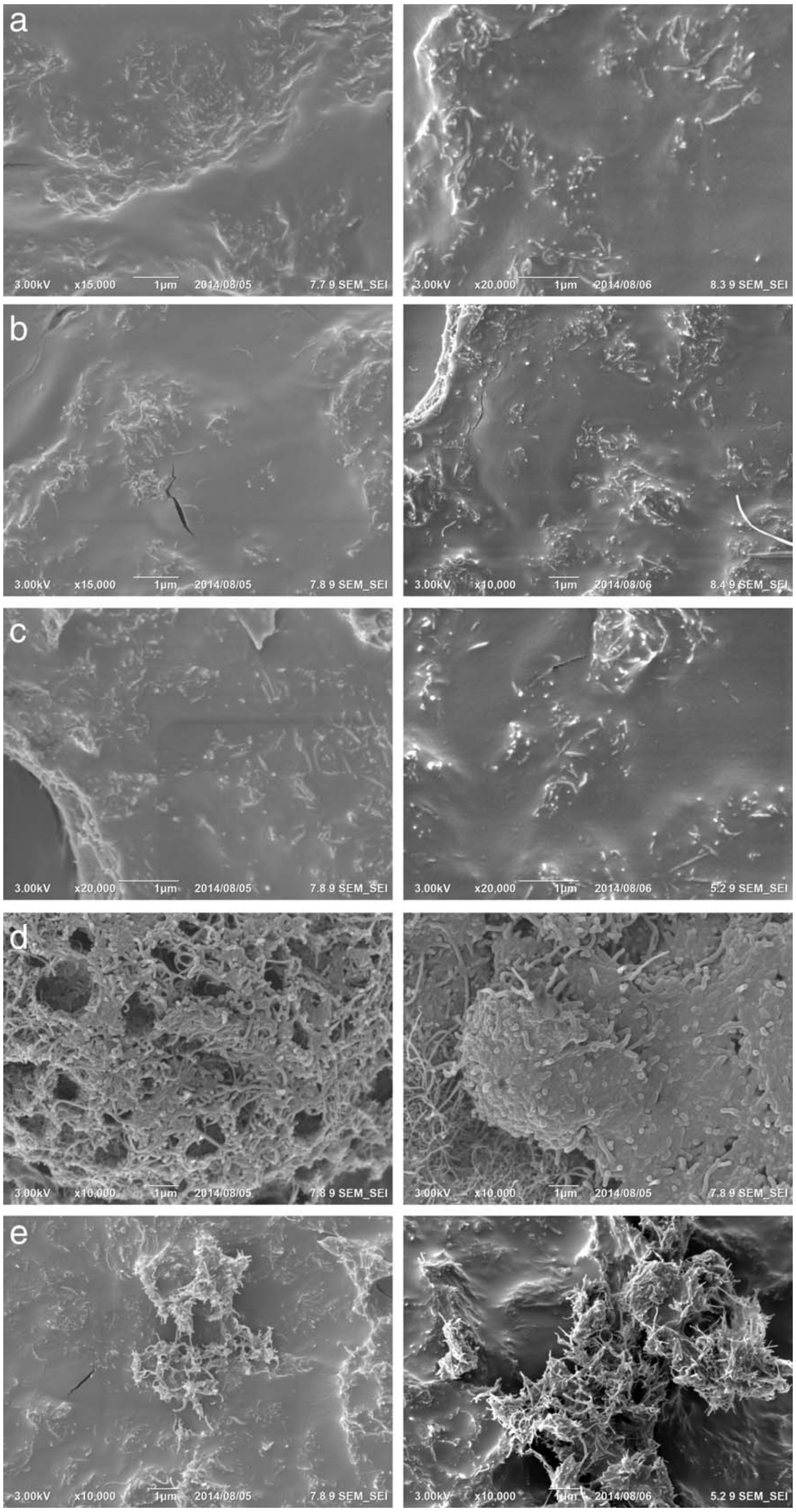

Figure 5. SEM images of PMMA with 1.5 wt % MWCNT and different laser feed angles with the flow direction (left, produced by CNC milling; right, produced by EDM).

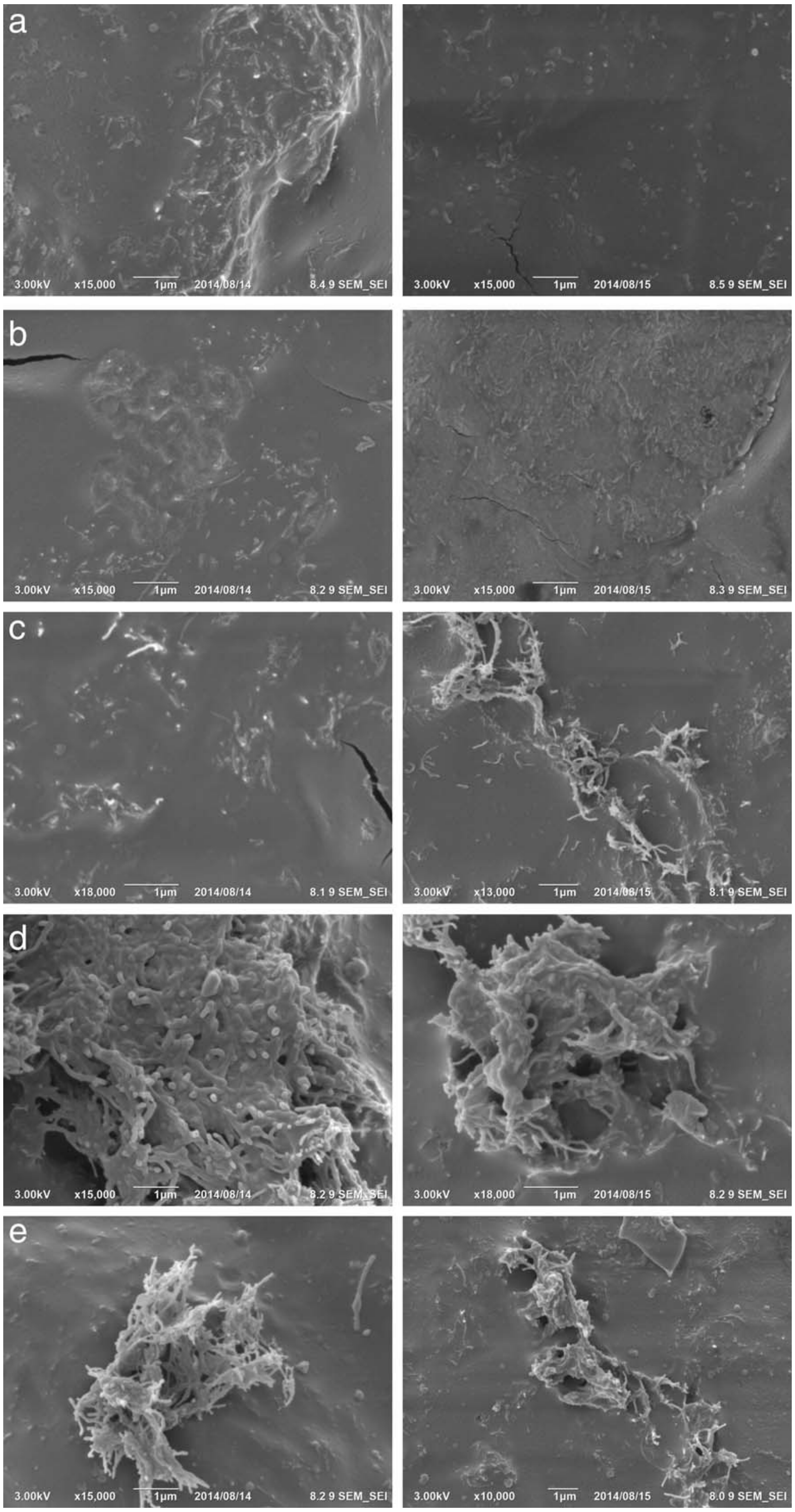

Figure 6. SEM images of PMMA with 0.5 wt % MWCNT and different angles with the flow direction (left, produced by CNC milling; right, produced by EDM).

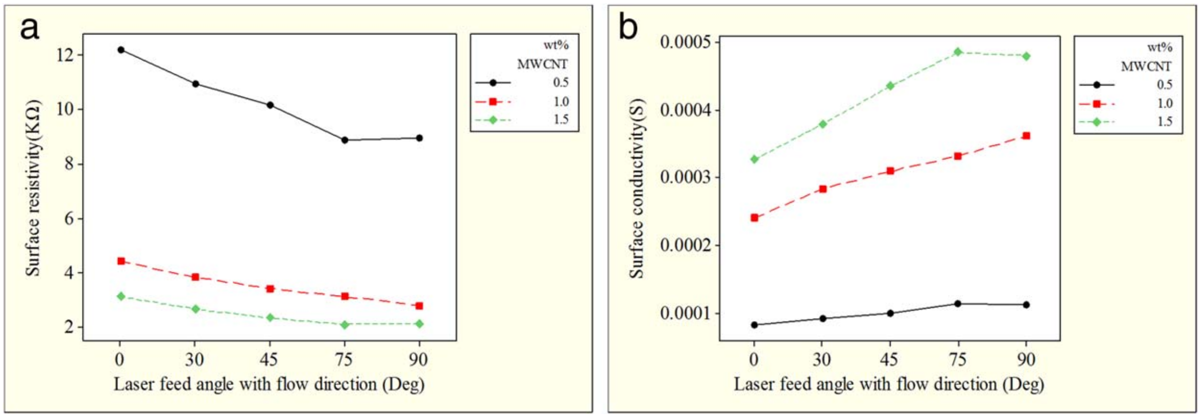

Figure 7. The interaction effect of laser feed angle and MWCNTs concentration (a) on the surface electrical resistivity and (b) on the surface electrical conductivity. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

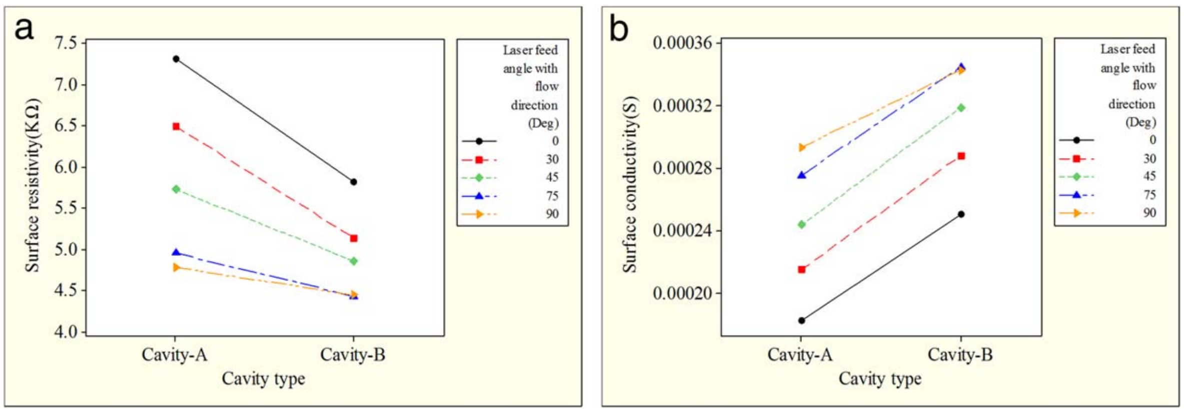

Figure 8. The interaction effect of cavity type and laser feed angle (a) on the surface electrical resistivity and (b) on the surface electrical conductivity. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

This phenomenon is attributed to the alignment of MWCNTs, as nanotubes tend to be partially aligned in the parallel to the flow direction in injection molding process.[15,25] With regard to CNT-based nanocomposites, electrons can be transferred by either the direct touching of nanotubes or the tunneling from one CNT to another, depending on the distance between the CNTs. In this way, the electrical conductivity is provided by CNT/polymer nanocomposite. It was uncovered that the minimum resistivity occurred with slightly aligned CNTs within the nanocomposite.[19,28] A slight increase in alignment tended to straighten the conduction paths and generated a greater number of junctions within the CNT/composite. Further alignment significantly reduced the percolation probability, which can be attributed to the reduction in the number of junctions and thus the decrease in the chance of CNT–CNT

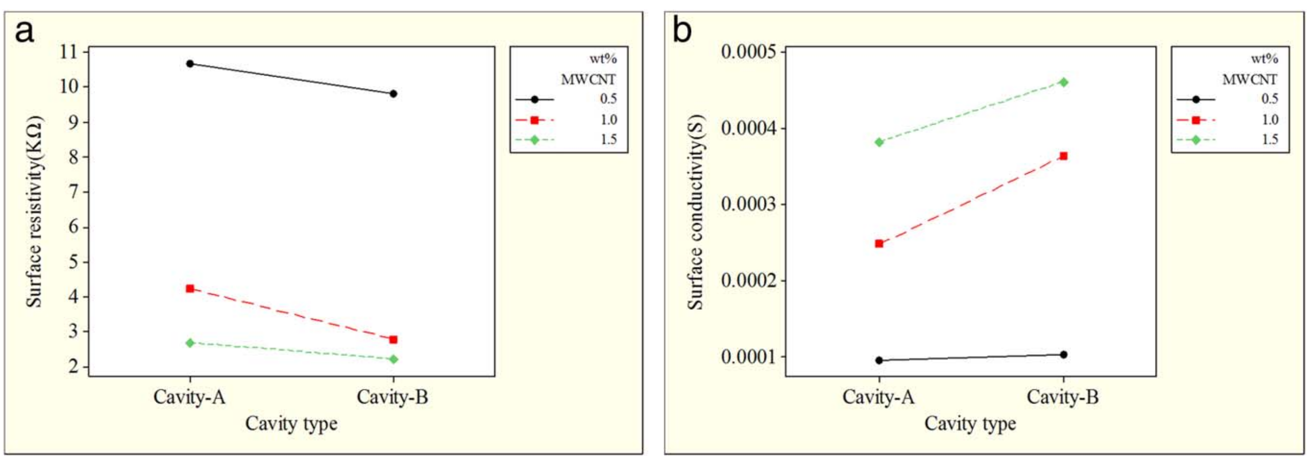

Figure 9. The interaction effect of cavity type and MWCNTs concentration (a) on the surface electrical resistivity and (b) on the surface electrical conductivity. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

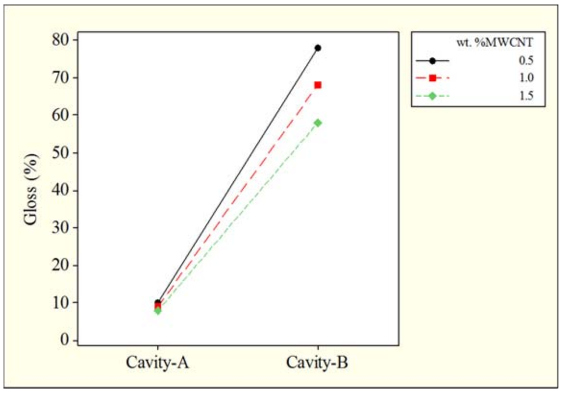

Figure 10. Effect of MWCNT and cavity machining type on surface gloss. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

intersections and the formation of conductive paths. A reduction in the alignment of CNTs can decrease the gap distance between nanotubes and increase the number of junctions, and therefore, the electrical conductivity of the nanocomposites increases. The axial angle of nanotubes intensely depends on the laser feed angle after laser process.

The irradiation of CO_2 laser beam melts the polymer base of nanocomposites. The nanotubes due to their high melting point do not melt. After that, the blast of covering gas bollixes the dispersion and alignment of CNTs. This condition leads to the enhancement of intersections and the reduction of gap distance between nanotubes, and consequently, it produces the network that can conduct the electrical current.

In the study conducted by Wichmann,[20] it was reported that CNT–CNT contacts with $\sim 75°$ axial angle create the minimum percolation threshold, which is in agreement with the results obtained in this study.

The interaction effect of mold cavity machining method and laser feed angle on the surface electrical resistivity and the surface electrical conductivity are shown in Figure 8(a,b), respectively. A partial reduction of resistivity is observed by change of cavity type. The produced nanocomposite by Cavity A (EDM) can partially enhance resistivity after laser process, which creates the rougher surface and reduces the gloss. Figure 9(a,b) shows the interaction effect of cavity type and MWCNTs concentration on the surface electrical resistivity and the surface electrical conductivity, respectively.

The measured amounts of surface gloss for different type of studied samples are demonstrated in Figure 10. As can be seen in Figure 10, the nanocomposites containing higher MWCNT concentrations have the lower gloss. Moreover, the use of EDM dramatically reduced the surface gloss. The surface with lower gloss adsorbs higher laser beam, and consequently, the generated heat increases. It seems that the higher melt temperature reduces the fluidity and improves the CNTs dispersion,[26,27] and thus, it confines the enhancement of contact between CNTs; therefore, the produced nanocomposites with Cavity A have lower electrical conductivity.

The analysis of variance (ANOVA) method measures the effect of input variables on the response variables through the relationship between these two families of variables. ANOVA method also defines which input parameters highly affect the quality feature statistically. The ANOVA results of the electrical resistivity of the PMMA/MWCNT nanocomposites are shown in Table IV. The results show that the laser feed angle and the percentage of MWCNT have statistical effect on the R_s at the 95% confidence level. The results also indicate that F values of the processing parameters calculated from experimental results are 2137.54, 48.15, and 75.55 for MWCNT concentration, feed rate angle with the flow direction, and cavity type, respectively. As the F value obtained from related statistical calculation is higher than theory F, it could be concluded that MWCNT concentration, feed rate angle with the flow direction, and cavity type could be found as the effective parameters on electrical resistivity. From the percent effect column of Table IV, it could be concluded that the percentage of MWCNT is the most effective parameter on the R_s of the PMMA/MWCNT nanocomposites. Then, the cavity type is found to be effective on the R_s. Another important result that could be obtained from ANOVA is the experimental F values of interaction between parameters are all higher than F values obtained from related statistical calculation, and therefore, the interaction between each two input parameters would be effective on R_s of laser-irradiated samples.

Regression

The regression model to represent the mathematic model among surface electrical resistivity (R_s) and various controllable input parameters of this research has been developed by regression analysis. Because of the significant effect of all input parameters, the regression equation of R_s was taken as a

Table IV. Analysis of Variance

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P-value	$F_{(DF,8,0.05)}$	Percent effect
M	2	356.799	356.799	178.399	2137.54	0.000	4.46	93.768
θ	4	16.075	16.075	4.019	48.15	0.000	3.84	2.112
C_t	1	6.306	6.306	6.306	75.55	0.000	5.32	3.314
$M \times \theta$	8	4.387	4.387	0.548	6.57	0.008	3.44	0.288
$M \times C_t$	2	1.196	1.196	0.598	7.17	0.016	4.46	0.314
$C_t \times \theta$	4	1.537	1.537	0.384	5.60	0.032	3.84	0.201
Error	8	0.668	0.668	0.083	–	–	3.44	–
Total	29	386.967	$S = 0.288895$		$R^2 = 99.83\%$		R^2(adj.) = 99.37%	

Adj SS, adjusted sum square; DF, degrees of freedom; SS, sum square; MS, mean square

Table V. Estimated Regression Coefficients for Equation (4)

Term	Coefficient SE	Coefficient	T	P
Constant	−1.58166	0.212091	−7.4574	0.000
csch (MWCNT)	0.07248	0.001861	38.9479	0.000
Angle × csch (MWCNT)	−0.01390	0.001184	−11.7326	0.000
Summary of model	S = 0.345466	R^2 = 99.27%	R^2(adj.) = 99.15%	R^2(predicate) = 98.70%

Table VI. Estimated Regression Coefficients for Equation (5)

Term	Coefficient SE	Coefficient	T	P
Constant	41.4435	4.64025	8.9319	0.000
Arcsch (MWCNT)	−9.9058	1.04832	−9.4492	0.000
csch (MWCNT)	0.1449	0.00842	17.2028	0.000
Angle × csch (MWCNT)	−0.0075	0.00082	−9.0699	0.000
Summary of model	S = 0.240506	R^2 = 99.65%	R^2(adj.) = 99.56%	R^2(predicate) = 99.22%

Table VII. Analysis of Variance for Equation (4)

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P-value	$F_{(DF,12,0.05)}$
Regression	2	194.650	194.650	97.325	815.48	0.000	3.88
csch (MWCNT)	1	181.041	181.041	181.041	1516.94	0.000	4.75
Angle × csch (MWCNT)	1	16.429	16.429	16.429	137.65	0.000	4.75
Error	12	1.432	1.432	0.119	-	-	2.69
Total	14	196.082		Durbin-Watson statistic = 1.85585			
				D_P = 4.50%			

Adj SS, adjusted sum square; DF, degrees of freedom; SS, sum square; MS, mean square

function of MWCNT concentration, laser feed rate angle with the flow direction, and cavity type. As two equations for produced nanocomposite in manufactured cavity by EDM [eq. (2)] and CNC milling and finishing process [eq. (3)] were considered, their terms were ascertained after statistical and mathematical study of behavior of variable input parameters.

$$R_s = A + B \cdot \text{csch } M + C \cdot \theta \cdot \text{csch } M, \quad (2)$$

$$R_s = A + B \cdot \text{csch}^{-1} M + C \cdot \text{csch } M + D \cdot \theta \cdot \text{csch } M, \quad (3)$$

where M is MWCNT concentration, θ(rad) is laser feed rate angle with the flow direction, and A, B, and C are constant impacts. The regression equations of the fitted model for the R_s (KΩ) are represented by the following equations:

$$R_s = -1.58166 + 0.0724809 \cdot \text{csch } M - 0.013896 \cdot \theta \cdot \text{csch } M, \quad (4)$$

$$R_s = 41.4435 - 9.09577 \cdot \text{csch}^{-1} M + 0.14486 \cdot \text{csch } M - 0.007478 \cdot \theta \cdot \text{csch } M. \quad (5)$$

Tables V and VI indicates the estimated regression coefficients for eqs. (4) and (5), respectively. The P-value amounts are less than α-level (0.05), and it reveals that all of the picked terms are affected. The R^2 value is defined as the ratio of variability explained by the model to the total variability in the actual data and is used as a measure of the goodness of fit. The more the R^2 value approaches unity, the better the model fits the

Table VIII. Analysis of Variance for Equation (5)

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P-value	$F_{(DF11,0.05)}$
Regression	3	183.119	183.119	61.0396	1055.26	0.000	3.59
Arcsch (MWCNT)	1	162.585	162.585	5.165	89.29	0.000	4.84
csch (MWCNT)	1	15.775	15.775	17.1178	295.94	0.000	4.84
Angle × csch (MWCNT)	1	4.758	4.758	4.7583	82.26	0.000	4.84
Error	11	0.636	0.636	0.0578	-	-	2.82
Total	14	183.755		Durbin-Watson statistic = 1.56072			
				D_P = 3.42%			

experimental data. The value of R^2(predicate) indicates the prediction capability of the regression model. All of the calculated R^2 values are more than 98%, which displays that the considered models have high adequacy.

ANOVA for the adequacy of the model is shown in Tables VII and VIII. The comparison between theory F and calculated F exhibits that the terms and regression model have high accuracy. In addition, Durbin-Watson statistic for eqs. (4) and (5) obtained 1.8558 and 1.5607, respectively, indicating that it eventuates autocorrelation. Another model precision characteristic is the percentage of differential between regression and experimental results, which was defined as D_P. Two models are with very low D_P, and therefore, they have an acceptable precision.

CONCLUSIONS

The utilization of CO_2 laser processing to improve the surface electrical conductivity of nanocomposite containing MWCNTs was investigated. MWCNT concentration, laser feed angle with the flow direction, and cavity type of mold were considered as variable input parameters.

The results show that CO_2 laser processing is a novel method, which can be used for the reduction of surface electrical resistivity of CNT-based composites. The morphology of laser-irradiated samples obviously depicted that the performed process led to bollix the primary alignment and dispersion of CNTs. The aggregated network of CNTs was formed, and the distance between them was reduced. In addition, the maximum density of network is attributed to the laser feed angle at 75°.

The significant increase of surface electrical conductivity of laser-irradiated samples was observed. The existence of direction relationship was demonstrated between MWCNT concentration and electrical conductivity. The investigations have revealed that laser beam feed angle is an effective parameter on surface electrical conductivity. The increasing of angle with the flow direction up to 75° enhances the electrical conductivity, but by increasing from 75° to 90°, and it slightly decreases due to the creation of agglomerated MWCNT bundles.

The effect of cavity machining method is another important factor on electrical properties after laser processing. The samples produced by electrodischarge machined cavity showed the higher resistivity.

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