International Nano Letters (2018) 8:137–145
https://doi.org/10.1007/s40089-018-0236-4

ORIGINAL ARTICLE

The effect of CNC and manual laser machining on electrical resistance of HDPE/MWCNT composite

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Received: 1 November 2017 / Accepted: 21 April 2018 / Published online: 24 May 2018

Abstract

In this study, electrical conductivity of high-density polyethylene (HDPE)/multi-walled carbon nanotube (MWCNT) composite was investigated after laser machining. To this end, produced using plastic injection process, nano-composite samples were laser machined with various combinations of input parameters such as feed rate (35, 45, and 55 mm/min), feed angle with injection flow direction (0°, 45°, and 90°), and MWCNT content (0.5, 1, and 1.5 wt%). The angle between laser feed and injected flow direction was set via either of two different methods: CNC programming and manual setting. The results showed that the parameters of angle between laser line and melt flow direction and feed rate were both found to have statistically significance and physical impacts on electrical resistance of the samples in manual setting. Also, maximum conductivity was seen when the angle between laser line and melt flow direction was set to 90° in manual setting, and maximum conductivity was seen at feed rate of 55 mm/min in both of CNC programming and manual setting.

Keywords Laser machining · High-density polyethylene · Multi-walled carbon nanotube · Composite · Electrical resistance

Introduction

The discovery of carbon nanotubes led to extensive scientific research activities ending up with various applications for these materials. More recently, the use of carbon nanotube (CNT), especially MWCNT, in polymer-based composites has been prospered because of its unique features such as low density, high electrical and thermal conductivity, high tensile strength, high elastic modulus, and lack of skin effect. One of the most popular applications of MWCNT is in electrical industries where they provide high electrical and heat conductivities.

Carbon dioxide laser (CO_2 laser) is one of the earliest developed, yet most useful lasers in the polymer industry. Due to its relatively high power and low price, the CO_2 laser is widely used in various applications such as cutting, welding, and engraving operations on such materials as woods, glasses, and polymers.

Because of the important role played by MWCNT in the production process of conductive polymer-based composites, several studies have been done in this field. Karimzad Ghavidel et al. [1] investigated the effect of CO_2 laser machining on the surface electrical conductivity enhancement of injection-molded poly (methyl methacrylate)/MWCNT composite. The obtained results showed that CO_2 laser machining enhanced the MWCNT–MWCNT contacts, resulting in increased electrical conductivity. The morphology of laser-machined surfaces confirmed that the conductive network formed by CNT–CNT contacts can transfer electrical current. Peotschke et al. [2] studied the volume electrical resistivity of polyethylene (PE) and polycarbonate (PC)/MWCNT composite produced by the melt mixing method. The obtained results illustrated that the introduction of MWCNT reduces volume electrical conductivity of PC. Lekawa-Raus et al. [3] investigated electrical properties of CNT-based fibers and their future application(s) in electrical wiring. It was declared that, according to extremely light weight, high conductivity, high tensile strength, and reasonable cost, CNT-based wires can serve as good alternatives to copper and aluminum wires. Alsafee et al. [4] investigated electrical conductivity of epoxy/MWCNT and suggested that, as an insulator, epoxy was transformed to a semiconductor by adding MWCNT. Wang et al. [5] studied the effect of CNT particles on thermal, electrical, and mechanical properties of bismaleimide/CNT composite. They observed that longer CNT particles result in higher

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electrical and thermal conductivity. But, tensile strength and Young's modulus were seen to be independent of CNT particle length. Tang et al. [6] investigated fracture toughness and electrical conductivity of epoxy composite reinforcement with CNT and spherical particles. They found that MWCNT particles together with spherical particles not only had increased electrical conductivities of epoxy composites, but also adjusted its stiffness, strength, and fracture toughness. Ounaies et al. [7] investigated the effect of CNT particles on AC and DC electrical conductivity of polyimide-based composites using analytical modeling and numerical simulation. Nattapat et al. [8] used the laser machining to modify the surface of carbon fiber-reinforced composites. Tamrin et al. [9] studied the effect of laser on mechanical properties of spot welds of thermoplastic polymers. Tangwarodomnukun and Chen [10] investigated the laser ablation process of PMMA in various environments such as air, water, and ethanol. Rytlewski [11] used Nd:YAG laser process to metalize polymer-based composites. Varvani Farahani et al. [12] investigated the effect of laser ablation on the ZnO nanoparticle properties. Sudhakar Kurhekar and Apte [13] studied the geometrical parameters of optical micromachined surfaces.

As discussed, the main application of HDPE/MWCNT composite can be considered in printed circuit boards (PCB). In this case, the laser-processed path on the composite, which is conductive, can be considered as circuits. On the other hand, major problem seems to be the effect of parameters of laser-machining process on electrical conductivity of the laser-processed path on the composite.

In the present work, the effect of CNC and manual CO_2 laser machining together with various combination of input parameters such as feed rate, feed angle with injection flow direction, and MWCNT content on resulted electrical conductivity of HDPE/MWCNT composite was investigated. To this end, produced using plastic injection process, nano-composite samples were laser machined with various combinations of input parameters such as feed rate (35, 45, and 55 mm/min), feed angle with injection flow direction (0°, 45°, and 90°), and MWCNT content (0.5, 1, and 1.5 wt%). The angle between laser feed and injected flow direction was set via either of two different methods: CNC programming and manual setting. The novelty of current work can be considered as investigating the effect of CNC and manual laser machining, feed angle with injection flow direction, and MWCNT content on electrical resistance of HDPE/MWCNT composite.

Materials and methods

Materials

HDPE granules produced by Petrochemical Company of Iran were used as matrix of composite. MWCNT particles provided by Nano-material Research Company of Iran were used to reinforce the composites. Physical properties of the MWCNT particles are listed in Table 1.

To achieve a perfect mixture of the HDPE granules with MWCNT particles, extrusion process with two extruders was utilized. MWCNT particles were added to HDPE granules at 0.5, 1, and 1.5 wt%, and mixed mechanically. The mixed particles were dried at 170 °C and a ZSK-25 twin screw extruder (Werner & Pfleiderer Company, Germany) was then used to mix the HDPE/MWCNT particles. The extruded blends were then crushed into small particles and dried at 80 °C for 20 h. Finally, the crushed particles were plastic injected into the nano-composite sheets using a NBM HXF-128 plastic injection molding machine. The plastic injection process was executed according to ASTM D638 standard.

Laser-machining process

In the present work, the laser-machining process was carried out using a laser machine equipped with a 100 W continuous CO_2 laser (YM Laser Machine 70 WATTS MAX 10, 200–10800 nm). The laser-machining process was performed using various combinations of parameters such as feed rate (in three levels), angle between laser feed and injection flow direction (in three levels), and MWCNT content (in three levels). The laser-machining parameters and their levels are listed in Table 2. Full factorial design

Table 2 Input parameters of laser-machining process

Parameter	Symbol	Levels		
		Low	Medium	high
MWCNT content (wt %)	M	0.5	1	1.5
Angle between laser line and injected plastic flow direction (°)	θ	0°	45°	90°
Feed (mm/min)	F	35	45	55

Table 1 Specifications of prepared MWCNT particles

Property	Purity (%)	Outer diameter (nm)	Inner diameter (nm)	Length (μm)	True density (g/cm^3)	Special surface area (m^2/g)
Value	95	10–20	5–10	10–30	2.1	≥ 200

of experiment was used to investigate the effect of process parameters on electrical resistivity of the laser-machined lines.

The angle between feed line and injection flow direction was set using two different methods. In the first method, called CNC programming, the sample was fixed on a table with the laser machining being performed at an angle set by CNC programing. In the second method, called manual setting, the sample was rotated on demand manually, with laser machining being performed along a horizontal line.

In the first method, workpiece was fixed at the angle of $\theta = 0°$ on the desk. Indeed, path of machining lines were defined using curl application of laser machine. Afterward, the desired lines with specified length of 9 mm were automatically created on workpiece at three angle levels ($\theta = 0°$, 45°, 90°) and three feed rate levels (35, 45 and 55 mm/min).

In the second method, the workpiece was manually rotated to achieve desired angles. In this case, a horizontal line with a specified length of 9 mm was defined for laser machining. To bring the workpiece in an appropriate position for horizontal line machining ($\theta = 0°$), the workpiece was leaned through the horizontal edge of a bevel. Furthermore, to bring the workpiece in an appropriate position for vertical line machining ($\theta = 90°$), the sample was leaned through vertical edge of bevel. Finally, to create lines at 45°, first, a stencil was created in the edge shape of the workpiece. Then, the samples were positioned in this stencil and laser machined. Figure 1 illustrates the laser-machining setup.

Fig. 1 Laser-machining setup

Electrical resistivity measurement

After laser machining of HDPE/MWCNT samples, electrical resistivity of etched lines was measured using a two-probe multi-meter (HIOKI 3280-10). To this end, the laser-machined lines were cleaned before measuring electrical resistivity to ensure any dust and/or dirt is removed. Also, the electrical resistivity of designed probe was measured and subtracted from the electrical resistivity obtained from measuring the laser-machined line. To reduce possible errors, electrical resistivity measurements were repeated three times and the obtained values were averaged and reported as electrical resistivity of the sample.

Data analysis

Once finished with obtaining all of the results, as a powerful tool to solve statistical problems, Minitab software was utilized for data analysis. The analysis of variance (ANOVA) was used to identify the effective parameters and evaluate their effects. Then, based on signal-to-noise ratio plots, optimized levels of the parameters were found. Finally, the optimum results were verified using average value plots.

In ANOVA, significances of model and each data on output parameter are investigated. Furthermore, the effectiveness of each model factor and its associated error are evaluated. The most important parameter is the significance level (p factor), which is determined considering the predicted error. The predicted error is usually assumed 5% in experimental works, so that the p factor should usually be below 0.05. In cases where the percentage exceeds this value, the model is concluded to be insignificant, i.e., input parameters impose no significant effect on output ones.

The signal-to-noise ratio was used based on “smaller is better” strategy because the objective function, i.e., electrical resistance, was aimed to be minimized. The adjustment formula of it is as follow:

$$S/N = -10 \times \log\left(\Sigma\left(Y^2\right)/n\right). \tag{1}$$

Results and discussion

Investigating the obtained results, it was found that the addition of the MWCNT into the HDPE improves the conductivity of the resulting nano-composite after laser-machining process by forming a conductive network. The conducting mechanism was found to include in two parts: conductivity within the MWCNT and conductivity along the interface of two MWCNTs.

The conductivity within the MWCNT could be described using tight-binding approximation. In this method, charge carriers jump in atomic orbitals between adjacent atoms in a phenomenon called hopping. The required energy by the carrier to undertake such a phenomenon is known as hopping energy [14].

On the other hand, tunneling mechanism may occur at the interface of the two MWCNTs, wherein electrons pass through the potential barrier between the two MWCNTs which may further contain polymer, making the nano-composite a conductive medium. The required energy by the carrier to undertake such a phenomenon is known as tunneling energy [14].

It is important to note that the tunneling energy has direct relation with the distance between two MWCNTs. The smaller the distance between two MWCNTs, the lesser the tunneling energy. In addition, the hopping energy is known to be smaller than the tunneling energy. So, compared to tunneling mechanism, hopping mechanism results in faster electron transmission. As the two MWCNTs become very close to each other, the tunneling energy between two MWCNTs reduces and in very close distances of two MWCNTs, the conduction mechanism along the interface of them could change from tunneling to hopping [14].

It is worth noting that not only higher wt% of the MWCNTs tends to bring the them closer to each other, but also the heat from laser machining removes the HDPE barrier at the interface of MWCNTs and contributes into fall of the MWCNTs on the bottom of laser-machined grooves where its density increases. Thus, the interface distance between MWCNTs decreases which results in reduction of the tunneling energy between two MWCNTs or conversion of the conduction mechanism along the interface of them from tunneling to hopping. In both cases, it results in reduction of electrical resistance.

Undertaking experiments, it was found that the addition of MWCNT at 0.5 wt% is associated with no significant effect on electrical resistivity of the nano-composite, so that the obtained nano-composite was still non-conductor. Due to low density of the MWCNTs in this sample and thereby wide spacing among the nanotubes, no conductive network was formed, so that, considering electron transmission mechanisms, it can be stipulated that the electron transmission process had difficulty in being performed via quantum tunneling mechanism, making the medium remained non-conductive.

Table 3 shows the effects of F and θ parameters for the case where MWCNTs were added at 1 wt% as obtained via CNC programming. Furthermore, looking at ANOVA results, it is observed that the addition of MWCNTs to polyethylene at 1 wt% is of no statistically significant physical effect on electrical resistivity of the nano-composite. It is because the associated p values (significance level) with these factors were more than 0.05.

Table 4 indicates the effect of F and θ parameters for the case where MWCNTs were added at 1.5 wt% as obtained via CNC programming. According to the Table 4, the only factor imposing a statistically significant physical impact on electrical resistivity of the samples was feed, because the associated p value (significance level) with this factor only was less than 0.05. According to ANOVA results, the addition of MWCNTs at 1.5 wt% was seen to impose statistically significant physical effects on electrical resistivity of the nano-composite. Thus, the trend of changes in electrical resistivity with changes in F parameter can be considered.

Table 5 presents the effects of F and θ parameters for the case where MWCNTs were added at 1 wt% as obtained via manually set machining. As can be observed, neither θ nor F exhibited any statistically significant physical effect on electrical resistivity of the nano-composite sample.

According to Table 6 that reports the results of ANOVA on the samples containing MWCNTs at 1.5 wt% and under manually set machining, the F and θ parameters were both found to have statistically significant physical impacts on electrical resistivity of the samples, because the associated p values (significance level) with these factors were below 0.05. Thus, the trend of changes in electrical resistivity with changes in F and θ parameters can be considered.

Figure 2 presents signal-to-noise ratios for experimental setup of CNC programming. According to Fig. 2, the optimal concentration of the MWCNT content was seen to be

Table 3 ANOVA for dataset of HDPE/1 wt% MWCNT composite based on experimental setup of CNC programming

Source	*DF*	SS	MS	*F*	*p*
Feed (mm/min)	2	300.32	150.16	2.42	0.205
θ (°)	2	147.92	73.96	1.19	0.393
Error	4	248.23	62.06		
Total	8	696.47			

Table 4 ANOVA for dataset of HDPE/1.5 wt% MWCNT composite based on experimental setup of CNC programming

Source	*DF*	SS	MS	*F*	*p*
Feed (mm/min)	2	1.77007	0.88503	11.60	0.022
θ (°)	2	0.93007	0.46503	6.10	0.061
Error	4	0.30507	0.07627	–	–
Total	8	3.00520	–	–	–

Table 5 ANOVA for dataset of HDPE/1 wt% MWCNT composite based on experimental setup of manual

Source	*DF*	SS	MS	*F*	*p*
Feed (mm/min)	2	1.740	0.870	0.55	0.616
θ (°)	2	5.233	2.617	1.65	0.301
Error	4	6.350	1.588	–	–
Total	8	13.324	–	–	–

Table 6 ANOVA for dataset of HDPE/1.5 wt% MWCNT composite based on experimental setup of manual

Source	*DF*	SS	MS	*F*	*p*
Feed (mm/min)	2	1.94302	0.97151	33.88	0.003
θ (°)	2	0.41002	0.20501	7.15	0.048
Error	4	0.11471	0.02868	–	–
Total	8	2.46776	–	–	–

the third tested level, i.e., 1.5 wt%. As such, it is clear that, with further increasing the content of the MWCNT, those will have increased contacts with one another, considerably reducing MWCNT alignments, which in turn results in reduced electrical resistivity. Therefore, electron transmission is performed by hopping mechanism. In addition, it is clear that optimal level of feed parameter is presented by the third tested level: 55 mm/min.

Figure 3 shows signal-to-noise ratios associated with manually set machining. According to Fig. 3, optimal level of MWCNT content was found to be the third tested level: 1.5 wt%. With increasing the content of the nanotubes beyond this level, those will have increased contacts with one another, considerably reducing MWCNT alignments, which in turn results in reduced electrical resistivity. Also, it is seen that the optimal feed rate is 55 mm/min, with the

Fig. 2 Signal-to-noise ratio plot for experimental setup of CNC programming

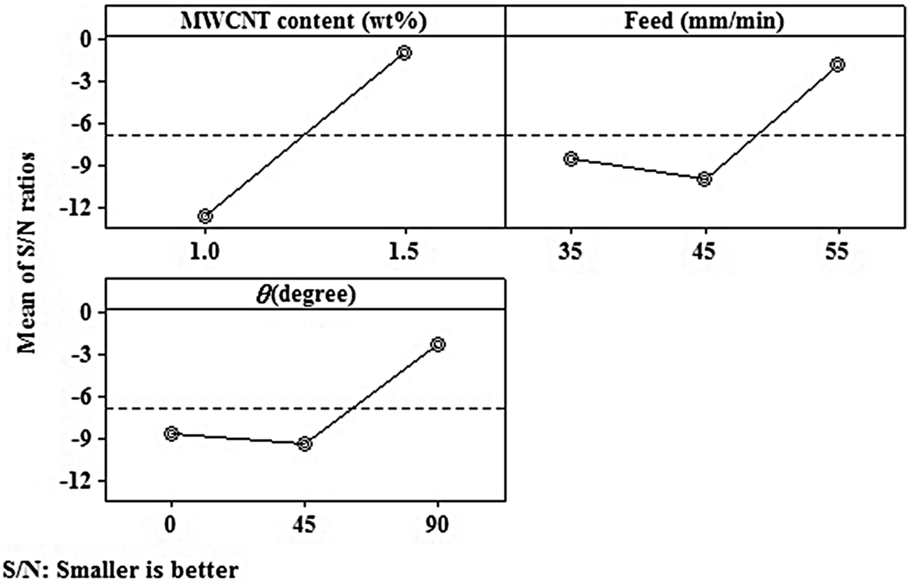


Fig. 3 Signal-to-noise ratio plot for experimental setup of manual

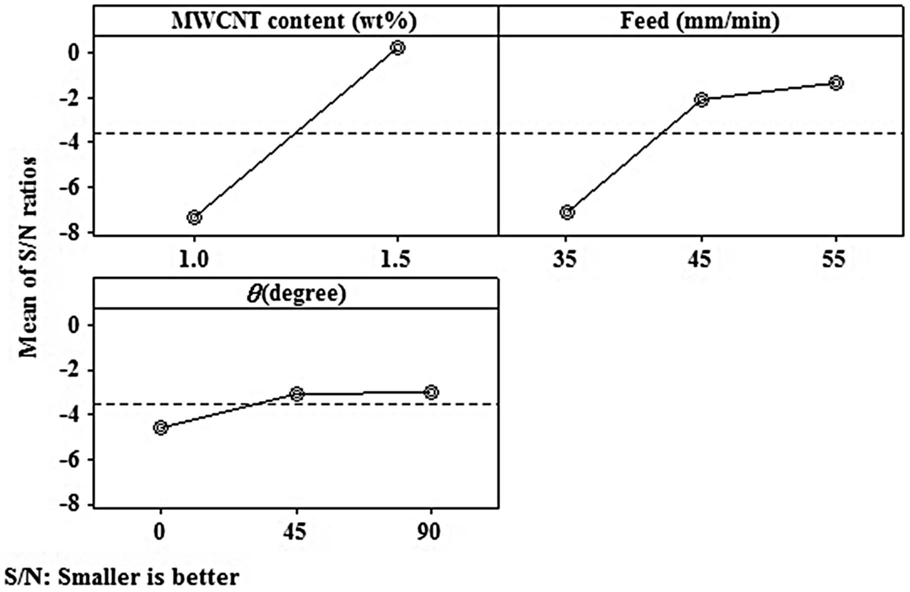
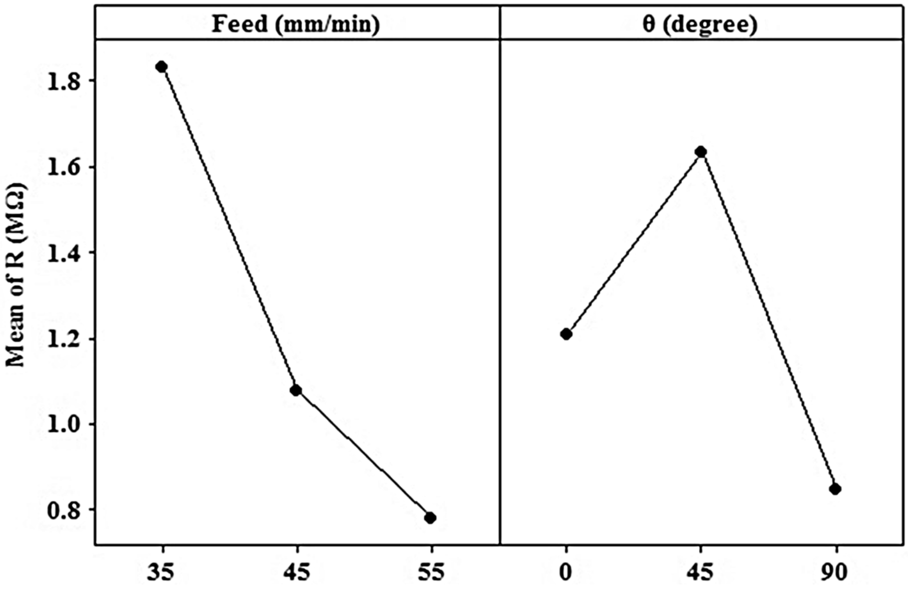


Fig. 4 The main effect diagram of feed and θ parameters on the electrical resistance for laser machining of HDPE/1.5 wt% MWCNT based on manual setup



θ confirming the optimality of third tested level, i.e., 90°. Based on MWCNT content, the alignment of nanotubes contributes to reduced collisions among which affects the penetration threshold significantly. Therefore, necessary nanotube content represents a significant factor when it comes to the establishment of a conductive network and electrical conductivity of the nanotube-containing composite. Thus, a reduction in carbon nanotube alignment can decrease spacing of the carbon nanotube particles, thereby increasing the number of links and, consequently, decreasing electrical resistivity of the nano-composite.

As can be seen from Figs. 2 and 3, optimal feed level was observed to be 55 mm/min. As higher feed rate tends to shorten the time required to laser-machined groove, it is associated with smaller loss of nanotubes. Therefore, the nanotubes within the groove will be of higher density and thereby forming larger sectors, i.e., electrical conductivity is improved. Finally, according to Figs. 2 and 3, optimal value of the angle between laser line and melt flow direction was 90°. This is because the maximum density of the conductive network is aligned at $\theta = 90°$. This result illustrates that the conductive network exhibits maximum density when the angle between laser line and melt flow direction is 90°, in which condition electron transmission is performed way simpler, maximizing the electrical conductivity.

Figure 4 shows interactive effects of progress rate and angle on electrical resistivity of the sample containing MWCNTs at 1.5 wt% with manually set laser machining. According to this plot, electrical resistivity reduces with an increase in feed rate. On the other hand, maximum electrical resistivity was obtained at maximum level of the angle parameter (θ). As can be seen on this plot, minimum electrical resistivity was that at the progress rate and angle of 55 mm/min and 90°, respectively.

Figure 5 shows interactive effects of feed rate and angle on electrical resistivity of the sample containing MWCNTs at 1.5 wt% with laser machining using CNC programming. According to this plot, electrical resistivity reduces with an increase in progress rate and minimum electrical resistivity is that at the progress rate of 55 mm/min.

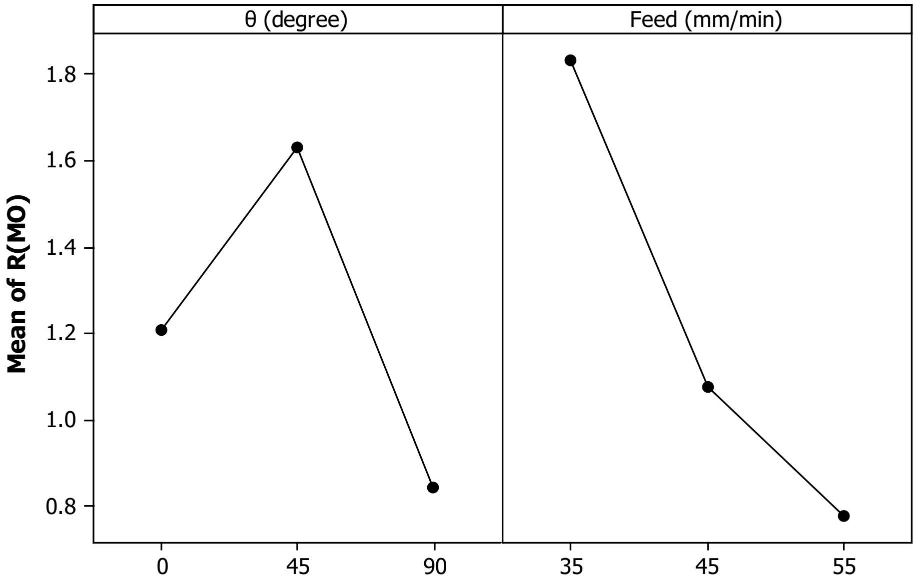
Microstructure evaluation via field-emission scanning electron microscopy (FESEM)

Figure 6 shows FESEM image of the cross section of 1.5 wt% MWCNT containing sample before laser machining. As seen from the figure, before laser-machining process, MWCNTs had less density within the composite. Considering the huge gap between MWCNTs keeping them from communicating with each other, electron transfer was supposed to be undertaken through quantum tunneling, developing a very high electrical resistivity.

Figure 7 illustrates the FESEM image of the laser-machined lines on 1.5 wt% MWCNT containing samples with 55 mm/min feed in terms of 90° for experimental setup of manual. By comparing Fig. 6 with Fig. 7, it can be concluded that performing laser-machining process on nano-composite samples enhanced the concentration of MWCNTs along the machining paths. Decreasing the gap between the MWCNTs because of enhanced concentration of MWCNTs seems to the result in conversion of electron-transfer mechanism from quantum tunneling to hopping mechanism.

Figure 8 illustrates the FESEM image of the laser-machined lines on 1.5 wt% MWCNT containing samples with 55 mm/min feed in terms of 0° for experimental

Fig. 5 The main effect diagram of feed and θ parameters on the electrical resistance for laser machining of HDPE/1.5 wt% MWCNT based on numerical control programming setup



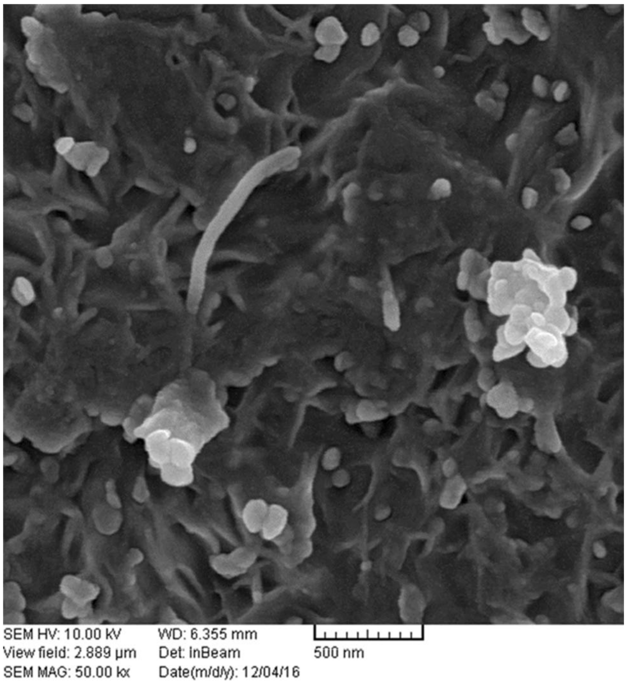


Fig. 6 FESEM of the cross section of 1.5 wt% MWCNT containing sample before laser machining

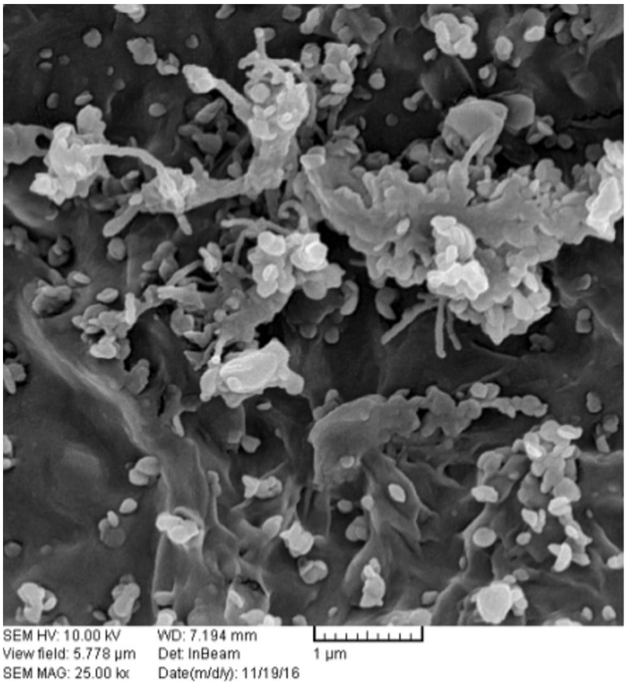


Fig. 7 FESEM of the laser-machined lines of 1.5 wt% MWCNT containing sample with 55 mm/min feed in terms of 90° for experimental setup of manual

setup of manual. It can be concluded that the size of the MWCNT clusters became smaller in Fig. 8 compared to Fig. 7. Increasing the gap between the MWCNTs because of smaller MWCNT clusters seems to result in electron transfer of hopping mechanism with higher electron-transfer-energy requirement, developing higher electrical resistivity. Thus, the electrical resistivity through laser-machined line of $\theta = 0°$ for experimental setup of manual became higher compared to that of $\theta = 90°$. Also, ANOVA tables and signal-to-noise charts further confirm this conclusion.

Figure 9 illustrates the FESEM of the laser-machined lines on 1.5 wt% MWCNT containing samples with 35 mm/min feed in terms of 90° for experimental setup of manual. Comparing Fig. 9 with Fig. 7, it can be concluded that, MWCNT clusters become larger with increase of feed rate. Increase of feed rate results in lower laser-machining operation and reduces the amount of heat applied. Thus, the MWCNT loss under the effect of laser operation's heat decreases with increase of feed rate. As a result, density of MWCNTs increases with increase of feed rate, decreasing the distance between the MWCNTs, so that electron transfer takes place well via hopping mechanism with lower electron-transfer energy. Indeed, it can be stipulated that, with increasing feed rate, conductivity of the laser-machined line increases.

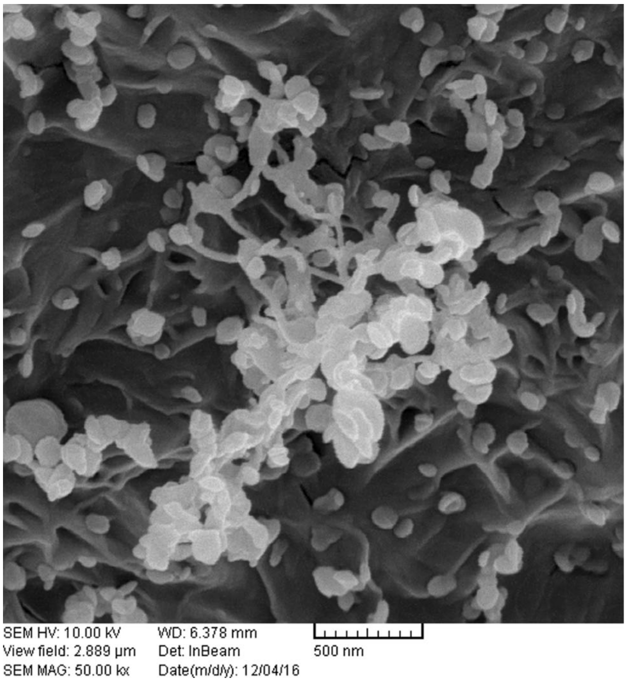


Fig. 8 FESEM of the laser-machined lines of 1.5 wt% MWCNT containing sample with 55 mm/min feed in terms of 0° for experimental setup of manual

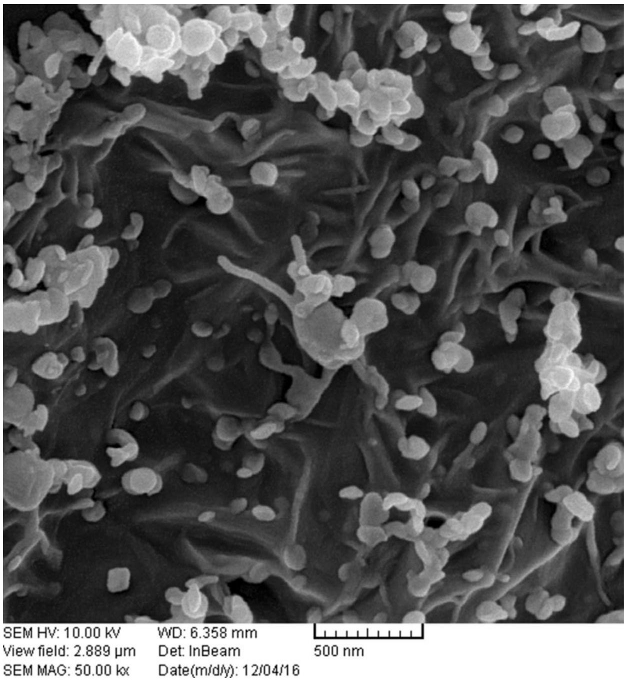


Fig. 9 FESEM of the laser-machined lines of 1.5 wt% MWCNT containing sample with 35 mm/min feed in terms of 90° for experimental setup of manual

Conclusions

In this study, the use of CO_2 laser machining to improve electrical conductivity of the HDPE/MWCNT composite prepared via the injection molding method was investigated. The machining process was performed in either of two modes: manual setting and CNC method. The results showed that:

1. CO_2 laser machining can be used to reduce electrical resistivity of PE/MWCNT composite. That is because laser radiation can change initial alignment and distribution of MWCNTs followed by the formation of compact networks of MWCNTs, wherein MWCNTs are spaced at smaller spacing.
2. 0.5, 1, and 1.5 wt% additions of MWCNTs to HDPE were seen to impose no significant effect on electrical resistivity of the nano-composite sample, leaving the sample non-conductive.
3. An increase in content of MWCNTs of nano-composite results in the accumulation of MWCNTs within the HDPE matrix and causes establishment of more contacts among MWCNTs, and facilitation of electron transmission via hopping mechanism; these ended up with reduced electrical resistivity after laser-machining process.
4. According to the obtained results, maximum conductivity was obtained with laser machining the samples containing MWCNTs at 1.5 wt%.
5. Maximum conductivity was seen when the angle between laser line and melt flow direction was set to 90°. This phenomenon shows that maximum conductive network density occurs at this angle.
6. Maximum conductivity was seen at feed rate of 55 mm/min. At higher feed rates, thermal loss of MWCNTs decreases as applied heat amount decreases with increase of feed rate. As such, electron transmission was facilitated via hopping mechanism with lower electron-transfer energy.
7. FESEM images from the cross section of 1.5 wt% MWCNT containing samples before and after laser

machining confirm the above results obtained from electrical resistivity measurements and ANOVA.

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