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Influence of processing condition and carbon nanotube on mechanical properties of injection molded multi-walled carbon nanotube/ poly(methyl methacrylate) nanocomposites

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ABSTRACT: In this work, multi-walled carbon nanotubes (MWCNT) and poly(methyl methacrylate) (PMMA) pellets were compounded via corotating twin-screw extruder. The produced MWCNT/PMMA nanocomposite pellets were injection molded. The effect of MWCNT concentration, injection melt temperature and holding pressure on mechanical properties of the nanocomposites were investigated. To examine the mechanical properties of the MWCNT/PMMA nanocomposites, tensile test, charpy impact test, and Rockwell hardness are considered as the outputs. Design of experiments (DoE) is done by full factorial method. The morphology of the nanocomposites was performed using scanning electron microscopy (SEM). The results revealed when MWCNT concentration are increased from 0 to 1.5 wt %, tensile strength and elongation at break were reduced about 30 and 40%, respectively, but a slight increase in hardness was observed. In addition, highest impact strength belongs to the nanocomposite with 1 wt % MWCNT. This study also shows that processing condition significantly influence on mechanical behavior of the injection molded nanocomposite. In maximum holding pressure (100 bar), the nanocomposites show highest tensile strength, elongation, impact strength and hardness. According to findings, melt temperature has a trifle effect on elongation, but it has a remarkable influence on tensile strength. In the case of impact strength, higher melt temperature is favorable. © 2016 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2016**, *133*, 43738.

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INTRODUCTION

The superior properties of carbon nanotubes (CNT), such as their low density, high aspect ratio, tensile strength, and extraordinary elastic modulus make them favorable fillers for the reinforcement of polymers. Polymeric CNT nanocomposites are applicable as the structural materials for automobiles and airplanes, due to their high strength to weight ratios. In addition, their high electrical conductivity makes them appropriate materials for electromagnetic interference (EMI) shielding and antistatic packaging.

There have been numerous reports on how addition of CNT fillers to polymer forms nanocomposites with enhanced properties in mechanical, thermal, and electrical aspects.[1] For effective reinforcement of polymers through the addition of nanotubes, four main system requirements are needed, namely a large aspect ratio, good dispersion, alignment, and interfacial stress transfer.[2] In addition, a large aspect ratio helps to transfer load to the reinforcing fibers.[3] An extensive amount of experimental and theoretical works in the literature has been devoted to investigating the effective properties of CNT/polymer composites. Because of many influential parameters, such as size, fabrication method, processing conditions, polymer characteristics, dispersion, and alignment of nanotubes, it is very difficult to generalize the results.[4] However, most of the works showed significant improvement in the properties of CNT-loaded composites compared to those of pure polymers. Several studies investigated the tensile strength and elasticity modulus of nanocomposites with MWCNT as a filler and polyethylene (PE), polycarbonate (PC) poly(methyl methacrylate) (PMMA), poly(vinyl alcohol) (PVA), and polypropylene (PP) as matrix.[1] PMMA is a glassy amorphous polymer with favorable mechanical properties, outstanding climate resistance, and excellent hardness. There have been several studies on PMMA/CNT nanocomposites prepared by *in situ* polymerization,[5] solution mixing,[6] and melt blending.[7,8] Jia *et al.*[5] have stated that the tensile strength of PMMA/CNTs were significantly increased by the incorporation of CNTs.

Unlike other techniques, melt mixing is the preferred method in industry. The nanocomposite preparation can affect its properties through changing alignment and dispersion of CNTs within polymer matrix. Low temperature and high shear mixing may enhance the dispersion of CNTs and minimize aggregates in the

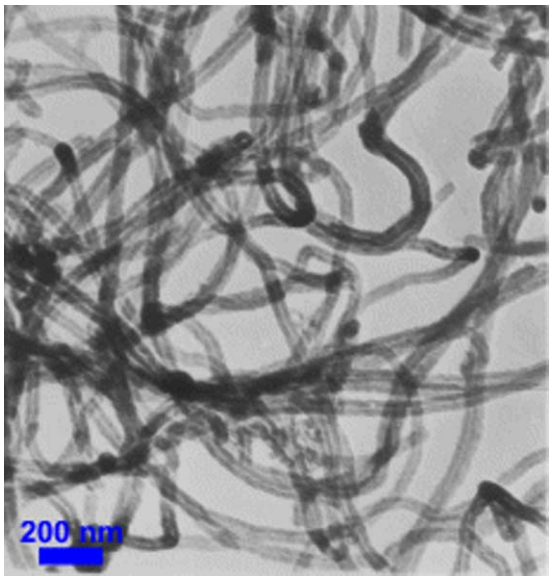

Figure 1. TEM image of the MWCNTs. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

composites.[9] Although a wide amount of researches have been carried out on the processing of CNT-filled polymeric nanocomposites, because of the high cost of CNTs, most researches have been performed with small samples produced in laboratory, so comparisons between the results and actual practical applications are limited. In industrial production processes, such as injection molding, there are significant effects of the processing parameters on the properties of the final product that cannot be fully assessed by small-scale laboratory research. Accordingly, there are still some challenges in terms of proper fabrication and characterization, particularly of injection molded nanocomposites. A review of the literature shows that only a few studies have focused on the fabrication of nanocomposites using an injection molding process.[10,11] Melt processing such as extrusion and injection molding have become a very popular technique for the fabrication of CNT-polymer composites due to its low cost and availability. Besides that, injection molding of polymeric nanocomposites is often used to fabricate a large quantity of complex components. In addition, the shear flow in the injection molding process significantly influences the alignment of CNTs in the molded parts that high alignment of CNTs in a particular direction is preferred in order to reach better tensile strength.[12]

Many researchers have reported that the elongation at break, which is an indicator of material toughness and flexibility, decreases when CNTs are incorporated in polymers.[13] The study by Abbasi *et al.*[12] also showed that elongation at break was reduced with the addition of nanotubes to the PC host. Agglomeration occurs due to poor dispersion, especially at the high concentration of nanotubes in a polymer matrix, which results in decreased mechanical strength.[14] Mathur *et al.*[15] reported that MWCNT/PMMA composite showed an increase in tensile strength about 9% at 0.5 vol % loading over the neat PMMA and approximately an increase of 7% was shown at 1 vol % loading. Gorga *et al.*[8] investigated mechanical properties of MWCNT/PMMA composites as a function of orientation, length and concentration using twin-screw extruder. They stated orientation of CNTs is the substantial factor to toughen nanocomposites and samples with long nanotubes are more effective for increasing tensile toughness. In addition, yield strength for samples with 0.1, 0.5, and 1 wt % CNT is lower than pure PMMA with a decrease of 10% in 1 wt %.

This work was adjusted on the produced nanocomposites using industrial scale equipment. To achieve this aim, the melt-mixing technique was used to disperse MWCNTs within PMMA matrix (without compatiblizer) by corotating twin-screw extruder and then the nanocomposite pellets were injection molded. The focus of this article is to investigate effects of processing parameters and nanotubes content on mechanical properties of MWCNT/PMMA nanocomposites. Melt temperature, holding pressure and nanotubes concentration are considered as variable parameters and tensile test, Rockwell hardness and charpy impact test of the nanocomposites were carried out and discussed.

EXPERIMENTAL

Materials

The PMMA pellets (CHI MEI Corporation, Taiwan) with the grade name of CM205, melt flow index (MFI) of 2.5 g/10 min (230 °C/5 kg) and density of 1.19 g cm^{-3} were used. The MWCNT powders were purchased from Nanostructured & Amorphous Materials (TX, USA) which were grown by the chemical vapor deposition (CVD) method with an outside diameter of 30–50 nm, an inside diameter of 5–15 nm, a length between 10 and 20 μm and purity more than 95%. Its density and aspect ratio are 2.1 g cm^{-3} and 200–666, respectively. Figure 1 shows the transmission electron microscopy (TEM) image of the obtained MWCNTs.

Mixing

Before mixing process, all the materials are dried in an oven at 80 °C for 4 h. First, the nanocomposite pellets are prepared in various carbon nanotube loadings with a ZSK25 corotating twin-screw extrusion. Screw speed of the extruder was set at 250 rpm and barrel zones temperatures were 200, 210, 230, 225, 230, and 220 °C, respectively.[9,16] The produced pellets are also dried at 80 °C for 24 h.

In the next step, the composites samples were produced using a NBM HXF-128 plastic injection molding machine with a length to diameter (L/D) ratio of 21.1 that its maximum injection pressure was 196 MPa. The constant injection molding parameters are tabulated in Table I.

Design of Experiments

Table II indicates the variable parameters and their levels. MWCNT concentration, melt temperature (which affects the mixing, flow,

Table I. Constant Parameters in Injection Molding Process

Parameters	Amounts	Units
Injection pressure	100	bar
Injection speed	67.2	mm/sec
Cooling time	15	sec
Holding time	2	sec
Mold temperature	28	°C

Table II. Levels of the Processing Parameters

Parameters	Levels				Symbol
MWCNT (wt %)	0	0.5	1	1.5	M
Melt temperature (°C)	240	250	260	—	T
Holding pressure (bar)	60	80	100	—	P

and orientation) and the holding pressure (which affects general product quality)[17] are considered as the variable parameters. Designs of experiment (DoE) are used by full factorial method and every experiment run is replicated three times that average of recorded data is reported as the result. Figure 2 displays fabricated specimens after injection molding. As can be seen in this figure, the samples of tensile test and impact test were produced based on ASTM D638-1 and ASTM D6110, respectively.

Tests

Tensile properties of the nanocomposites were studied under a strain rate of 5 mm/min at room temperature by Gotech Al-7000M. An Indentec universal hardness testing machine (Zwick/Roell, England) was employed in order to carry out the Rockwell H hardness tests. At least five points of a sample in the in-flow direction were examined and the average of recorded data reported as the Rockwell hardness results. In addition, notched samples were tested by Noavaran Baspar Charpy impact test machine. The notches were created by using NAB-NOTCH according to ASTM D 256.

RESULTS AND DISCUSSION

Morphology

The dispersion and alignment of nanotubes within a polymer matrix play a key role in the functional properties of CNT nanocomposites. In this regard, we have first characterized the dispersion and alignment of nanotubes using scanning electron microscopy (SEM). The SEM images (JEOL, Jib-4601f) of the nanocomposite cross section are shown in Figure 3 to certify dispersion and alignment of nanotubes within the PMMA matrix. According to these images, nanotubes are well dispersed in the polymer phase and the nanotube orientation is in the shear flow direction. Because the injection molding process exhibits high shear stress in the melt flow direction, the CNTs become partially aligned in the flow direction within the nanocomposites.[12] In addition, since the injected specimens were cut perpendicularly to the flow direction and head of CNTs appeared in the flow direction within the PMMA matrix in Figure 3, it is concluded that the nanotubes orientation is in the shear flow direction

Tensile Test

Main effects of the melt temperature, holding pressure and CNT concentration on yield tensile strength are plotted in Figure 4(a). According to this figure, carbon nanotubes existence has a significant effect on yield tensile strength. It can be also seen increasing of CNTs up to 1.5 wt % decrease the tensile strength about 30%, compared to pure PMMA. The decrease in the tensile strength of the samples can be explained by three main factors as (I) agglomeration of CNTs, (II) poor interfacial bonding between the CNTs and PMMA matrix, and (III) shortening of CNTs during extrusion and injection molding processes. When CNTs are not dispersed well within the polymer matrix, the agglomerated bundles can act as stress concentration locations which this can lower the yield strength of the nanocomposites. The poor interfacial bonding between the CNTs and PMMA phase is expected as no compatibilizer was used in this study. Finally, the shortening of nanotubes occurs due to the high rubbing and shearing forces in the extruder and injection molding machines.[18–20] To achieve better mechanical properties, it is essential that the CNTs should have a large length and acceptable alignment within polymer matrix. As such, reduction in length of CNTs reduces the aspect ratio and, consequently, weakens the reinforcement effects of nanotubes.[8] It is an important difference between CNT/polymer production in a large scale and laboratory techniques.

In the case of processing conditions, highest yield tensile strength is observed in minimum melt temperature (240 °C). The melt temperature decreasing can increase the melt viscosity and the shear force which leads to an increase in CNT alignment and also a decrease in numbers of agglomeration.[10] On the other hand, the increasing of melt temperature is also inappropriate factor for polymers, because it can reduce the binding force between mers and also diminish their length.[21] Also according to Figure 4(a), an increase in holding pressure leads to higher tensile strength. At a

Figure 2. The shape of fabricated samples after injection molding process. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

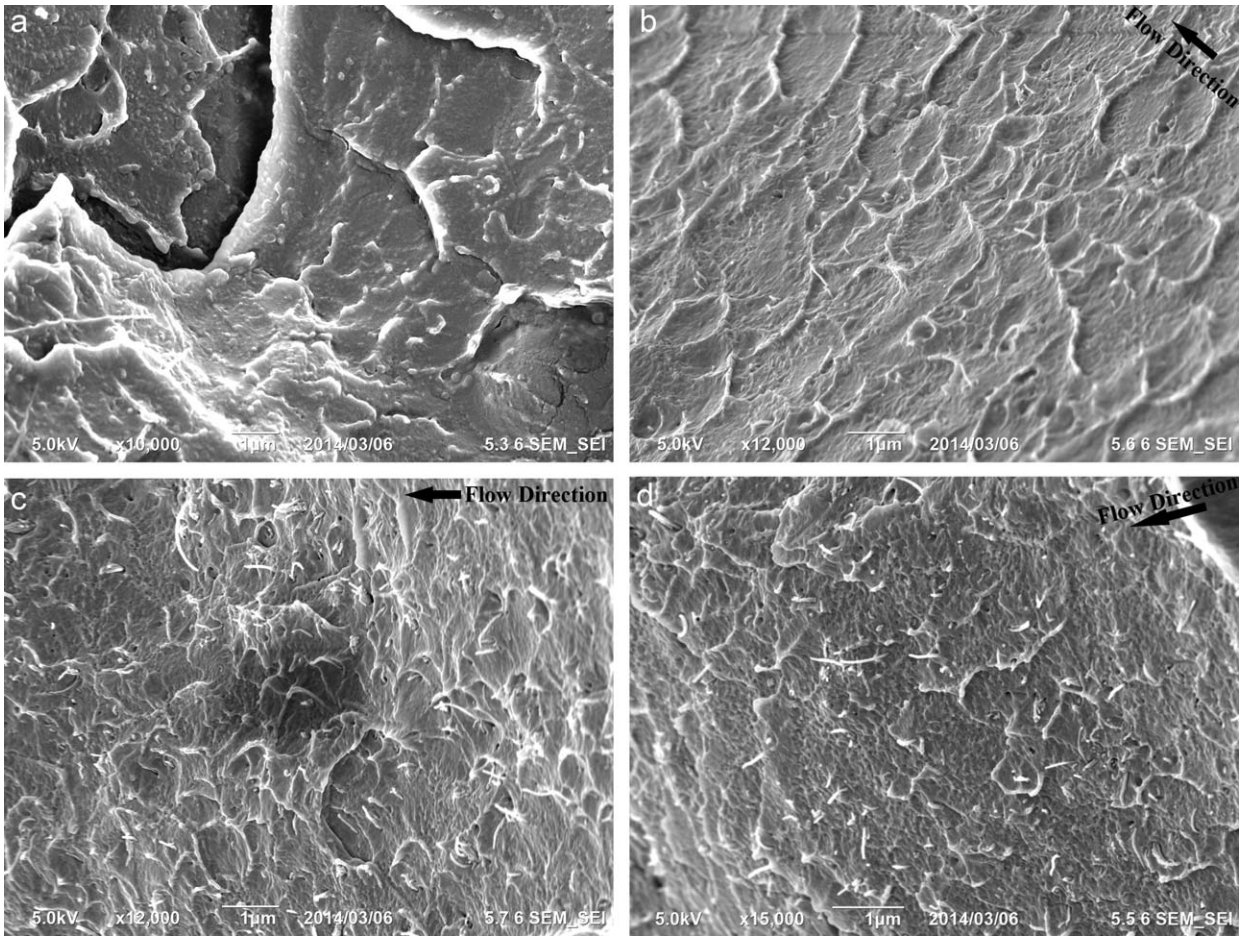

Figure 3. SEM images of the produced specimens. (a) pure PMMA (b) PMMA with 0.5 wt % MWCNT (c) PMMA with 1 wt % MWCNT (d) PMMA with 1.5 wt % MWCNT nanocomposite.

higher holding pressure, the defects of injected parts such as micro cracks and micro porosities are decreased.[22] Moreover, CNTs are more aligned in the in-flow direction and a higher strength can be achieved.[10]

The interaction of the parameters on the yield tensile strength of the nanocomposites is presented in Figure 4(b). It is observed in the nanocomposite containing 1.5 wt % CNTs, increasing holding pressure from 80 to 100 bar does not have a noticeable effect on yield point. This matter is also clear for the increasing of melt temperature from 250 to 260 °C. Thus, it can be concluded that in higher concentration, increasing the melt temperature and holding pressure are not effective for improving tensile strength. In the case of nanocomposites with lower CNTs loading (0.5 wt %), insignificant change is observed by increasing the temperature. This phenomenon can be attributed to existence of low agglomeration and better CNT distribution in lower concentration.[23] As it has been discussed, yield strength depends on the number of agglomerations. The number of produced agglomerations will be low when the CNT loading is low. Therefore, it can be concluded that decreasing temperature cannot be an effective parameter to improve the yield strength of nanocomposites.[10,14]

The analysis of variance (ANOVA) method is used to determine the effect of input variables on the output variables and defines which input parameters highly affect the quality feature statistically. The ANOVA results of the tensile strength are shown in Table III. As can be seen in this table, the amount of *R*-square is 93.45% that shows the considered analysis model has an acceptable level. The results also indicate that F values of the processing parameters (calculated from experimental results) are 140.90, 11.07, and 21.89 for MWCNT concentration, temperature and pressure, respectively. As the F value obtained from related statistical calculation is higher than theoretical F (from statistical tables),[24] it can be concluded that MWCNT concentration, melt temperature and holding pressure are the effective parameters on the tensile strength. Another important result that can be obtained from ANOVA is the *F* values of interaction between CNT content and the temperature, which is higher than theoretical F. Therefore, this interaction between two input parameters would be effective on the strength. Besides that, two other interactions have no significant effect. According to percent effects from Table III, MWCNT percentage with percent effect of 80.93% is the most effective parameter on the tensile strength.

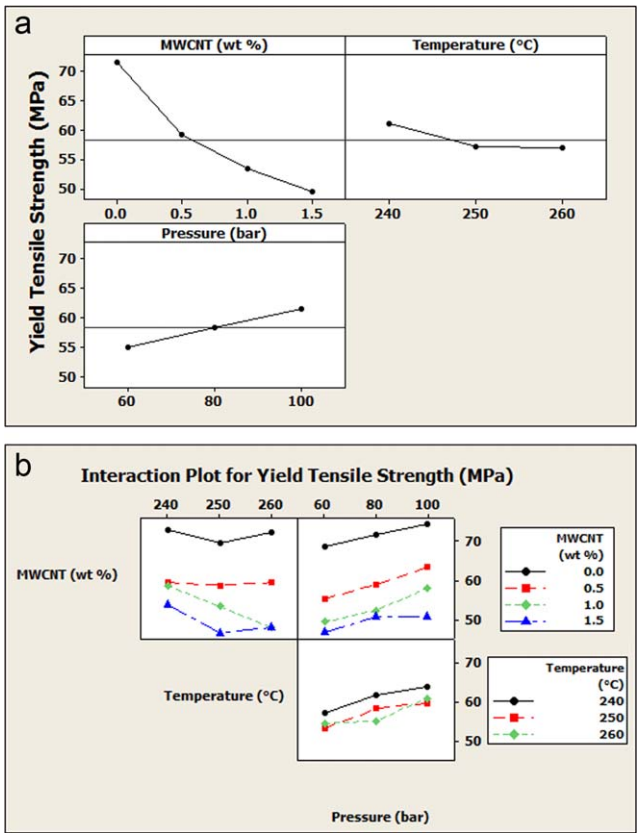

Figure 4. (a) Main effect plots (b) interaction plots of yield tensile strength. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

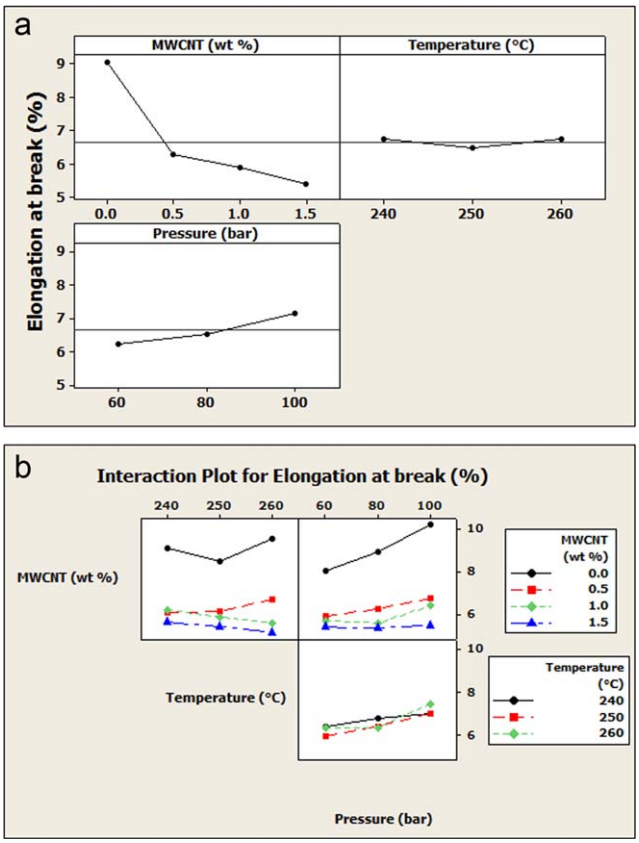

Figure 5. (a) Main effect plots (b) interaction plots of elongation at break. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The main effects of processing parameters and nanotubes content of the samples on elongation at break are shown in Figure 5(a). Elongation, which is an indicator of material toughness and flexibility, decreases by incorporating MWCNTs.[12] The maximum elongation amount is obtained for pure PMMA and the minimum amount is observed in nanocomposite with 1.5% CNTs. In general, adding of CNTs to PMMA matrix does not have positive influence on elongation. As it has been described in the case of yield strength, the agglomeration is an undeniable factor on behavior of nanocomposites. The effect of CNTs agglomeration can also be considered in reduction of elongation. Places where agglomerations of CNTs occur can be a potential defect zone for crack formation and, consequently these places debilitate mechanical properties such as elongation.[12]

Weak interfacial adhesion between CNTs and PMMA matrix can be the second powerful reason.[18] The increasing of thermal conductivity by CNTs increasing can be another reason for reduction of elongation. When the thermal conductivity is increased the cooling rate of samples is changed (change in residual stress) that

Table III. Analysis of Variance for Yield Tensile Strength

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P* value	$F_{(DF,12,0.05)}$	P_{eff}
M	3	2488.55	2488.55	829.52	140.90	0.000	3.49	80.93
T	2	130.39	130.39	65.19	11.07	0.002	3.88	4.24
P	2	257.75	257.75	128.88	21.89	0.000	3.88	8.38
M × T	6	134.91	134.91	22.49	3.82	0.023	3.00	4.39
P × M	6	33.83	33.83	5.64	0.96	0.492	3.00	1.10
T × P	4	29.57	29.57	7.39	1.26	0.340	3.26	0.96
Error	12	70.65	70.65	5.89				
Total	35	3145.66	S = 2.42638 R-Sq = 97.75% R-Sq(adj) = 93.45%					

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

Table IV. Analysis of Variance for Elongation at Break

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P* value	$F_{(DF,12,0.05)}$	P_{eff}
M	3	72.0817	72.0817	24.0272	212.38	0.000	3.49	84.4
T	2	0.5528	0.5528	0.2764	2.44	0.129	3.88	0.64
P	2	5.5005	5.5005	2.7502	24.31	0.000	3.88	6.44
M × T	6	2.6706	2.6706	0.4451	3.93	0.021	3.00	3.13
P × M	6	3.7165	3.7165	0.6194	5.48	0.006	3.00	4.35
T × P	4	0.8780	0.8780	0.2195	1.94	0.168	3.26	1.03
Error	12	1.3576	1.3576	0.1131				
Total	35	86.7577	S = 0.336351 R-Sq = 98.44% R-Sq(adj) = 95.44%					

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

can be effective on the elongation. As can be seen in Figure 5(a), melt temperature has a slight effect on elongation. Regarding holding pressure, tougher nanocomposites are observed in high pressures.

Interaction plots of the results are shown in Figure 5(b). According to this figure, in nanocomposites containing MWCNT, processing parameters make less change on elongation. In the nanocomposites with highest CNT concentration (1.5 wt %), increasing melt temperature and holding pressure do not have significant effect on elongation of the samples. These findings prove, when CNT concentration is increased the process parameters have a trifle effect on the CNT alignment because the effect of agglomeration is stronger.

The ANOVA results for elongation at break are shown in Table IV. Results reveal that percentage of MWCNT and holding pressure has statistically effect on the elongation with 95.44% *R*-square amount. The F value of the CNT content and the pressure are 212.38 and 24.31, respectively. Because these calculated F values are bigger than the theoretical F amounts (i.e., 3.49 and 3.88), the CNT percentage and the holding pressure are effective on elongation. Moreover, the examination of percent effects shows that the percentage of MWCNT ($P_{eff} = 84.4\%$) is the most effective parameter on the elongation.

Rockwell Hardness

Figure 6(a) depicts the main effect plots of variable parameters on the samples hardness. Low amount incorporation of MWCNTs has a minor effect on the hardness of the nanocomposites (0.5 wt %), but further increasing in CNT loading enhances the hardness. According to Figure 6(a), increasing the melt temperature in the injection molding process decreases the hardness. As it has been described in tensile strength part, the low temperature can help to improve dispersion of CNTs and decreasing agglomerations and consequently the hardness is increased.[21] However, the holding pressure is an effective parameter that its increasing improves the hardness. As it has been described in tensile test part, the holding pressure is a key parameter on the properties of injection molded parts. Increasing of holding pressure can decrease the internal defects and consequently, makes better properties.[22] In addition, when the injected material is CNT base nanocomposites, higher holding pressure assists to make better alignment that it can also be effective factor for reaching better properties.

Interaction plots of processing parameters are shown in Figure 6(b). As Figure 6(b) reveals, the maximum volume of hardness was resulted in low melt temperature. This result reveals that the high temperature is an unfavorable factor for hardness. As it has been mentioned in the tensile strength section, the melt viscosity and shear force increase in low melt temperature, which leads to an increase in CNTs alignment and decrease in number of agglomerations.[10] In addition, at highest level of holding pressure, changing nanotubes concentration shows

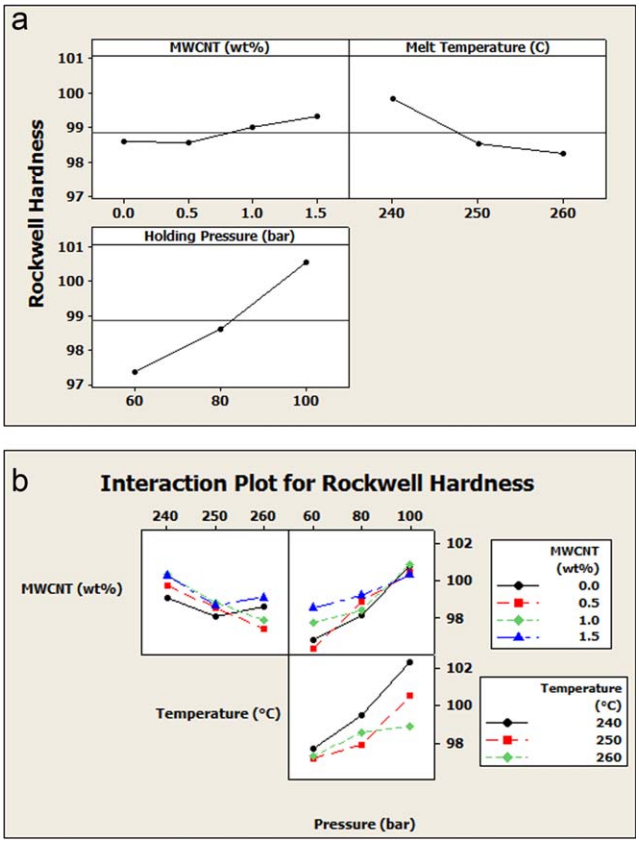

Figure 6. (a) Main effect plots (b) interaction plots of hardness. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table V. Analysis of Variance for Hardness

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P* value	$F_{(DF,12,0.05)}$	P_{eff}
M	3	3.6843	3.6843	1.2281	12.43	0.000	3.49	3.43
T	2	17.2162	17.2162	8.6081	87.13	0.000	3.88	16.04
P	2	62.7921	62.7921	31.3961	317.80	0.000	3.88	58.51
M × T	6	4.8841	4.8841	0.8140	8.24	0.001	3.00	4.55
P × M	6	6.9926	6.9926	1.1654	11.80	0.000	3.00	6.51
T × P	4	11.7488	11.7488	2.9372	29.73	0.000	3.26	10.95
Error	12	1.1855	1.1855	0.0988				
Total	35	108.5037	S = 0.314311 R-Sq = 98.91% R-Sq(adj) = 96.81%					

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

slight effects on the hardness, but varying melt temperature in this pressure has a prominent influence.

The ANOVA results of the hardness are shown in Table V. The results confirm that all input parameters have statistical effect on the hardness with *R*-square amount of 96.81%. The calculated F values for holding pressure, melt temperature and CNT percentage are 317.80, 87.13, and 12.43, respectively. The comparison between these amounts and theoretical F values shows that all input parameters are effective on hardness. The *F* values of the parameters intersection are also bigger than the theoretical *F* values. Therefore, they have significant effect on the hardness results. From percent effect column of Table V, it can be found that holding pressure is the most effective parameters on the hardness with percent effect of 58.51%.

Impact Test

Apart from elongation and strength, impact properties are crucial in polymer applications, which is related to fracture toughness. Main effects plot for impact strength of the notched samples in different levels of selected parameters is presented in Figure 7(a). As Figure 7(a) declares, the impact strength of specimens are improved up to 35%, while amount of MWCNTs is increased up to 1 wt %, but further increasing up to 1.5 wt %, reduces the impact strength. The carbon nanotube due to the folding property is a shock damper[25] and can absorb the part of shocks. As can be seen, adding of this reinforcer to the PMMA matrix (in nanometer size) could improve the impact strength. The dispersion and agglomerations have a key role on impact strength. When the CNT concentration is increased up to 1.5 wt %, achieving to a perfect dispersion is toil and the numbers of agglomeration are increased. Therefore, it is observed the amount of impact strength was decreased in 1.5 wt % MWCNT due to probably the presence of a lot of nanotube agglomerations in PMMA matrix, which provides point of stress concentration and sites for crack initiation. Another noticeable point is the huge effect of temperature in improving impact strength. This is evident that increasing the temperature exhibits reverse trend in comparison with tensile strength. In the impact test, the direction of entrance energy is perpendicular to flow direction, while in tensile test applied load is in the flow direction. It seems that when the alignment is weak in higher temperature and CNT networks were produced, the impact resistance of samples can be increased. Therefore, the impact resistance could be improved by melt temperature increasing. In general, as the produced nanocomposites are anisotropic, because of difference in applied load during tensile and impact tests, diverse manner can be seen.

Figure 7(a) also reveals the impact strength of specimens is improved in higher amounts of holding pressure. In the case of interaction plot to better showing of details in Figure 7(b), the noticeable point is changing melt temperature from 250 to 260 °C improves the impact strength of the nanocomposite with

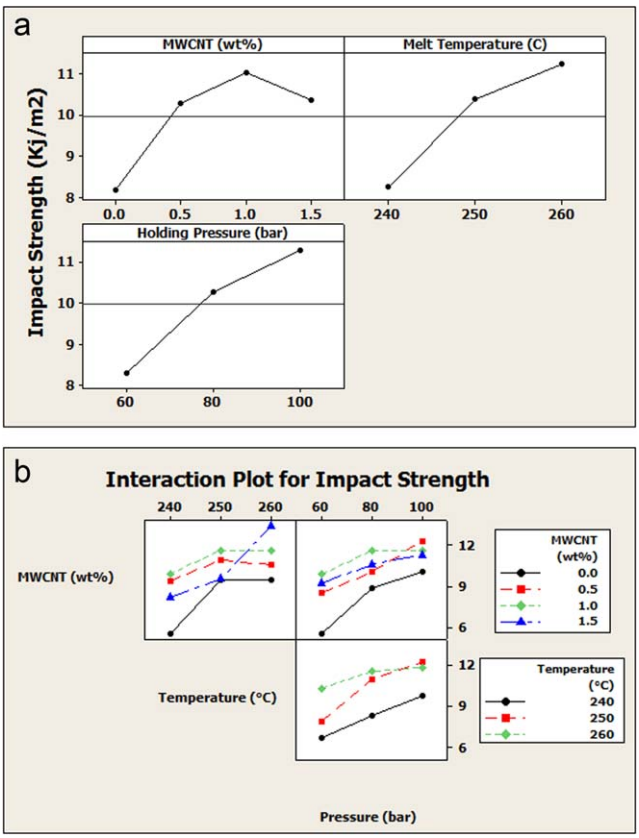

Figure 7. (a) Main effect plots (b) interaction plots of impact strength. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table VI. Analysis of Variance for Impact Strength

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P* value	$F_{(DF,12,0.05)}$	P_{eff}
M	3	41.2165	41.2165	13.7388	58.25	0.000	3.49	20.63
T	2	56.8263	56.8263	28.4132	120.46	0.000	3.88	28.44
P	2	55.9069	55.9069	27.9535	118.51	0.000	3.88	27.98
M × T	6	26.4017	26.4017	4.4003	18.66	0.000	3.00	13.21
P × M	6	10.5283	10.5283	1.7547	7.44	0.002	3.00	5.27
T × P	4	8.9340	8.9340	2.2335	9.47	0.001	3.26	4.47
Error	12	2.8305	2.8305	0.2359				
Total	35	202.6442	S = 0.485670 R-Sq = 98.60% R-Sq(adj) = 95.93%					

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

1.5 wt % MWCNT dramatically. However, in other contents it has a slight effect. In addition, pure PMMA samples in comparison with the nanocomposites containing MWCNTs show lower impact strength in different levels that this finding confirms the CNTs are useful particles for increasing the impact strength of PMMA.

The ANOVA results are shown in Table VI. All three selected parameters have statistically significant effect on impact strength of the nanocomposites with 95.93% R-square amount. As illustrated in Table VI, melt temperature, holding pressure and MWCNT percentage are important factors on the impact strength, because their calculated *F* values are bigger than theoretical *F* amounts. The *F* values of the intersections between input parameters are bigger than the theoretical *F* value, which means they have significant effect on the impact strength of the nanocomposites. Melt temperature, holding pressure, and percentage of MWCNT are found to be effective parameters on the impact strength respectively according to percent effect.

CONCLUSIONS

In this article, the effect of carbon nanotube content and injection molding processing conditions on mechanical properties of MWCNT/PMMA nanocomposite were studied. For this aim, compounding of MWCNT and PMMA nanocomposites pellets was prepared through twin-screw extruder and the test samples were fabricated using injection molding. The SEM images confirm the uniform dispersion of MWCNTs in the polymer matrix. Tensile tests, Rockwell hardness, and Charpy impact tests were carried out to investigate the effects of carbon nanotubes concentration, holding pressure, and melt temperature on mechanical properties of the nanocomposites using full factorial method.

The results showed that tensile strength and elongation at break of the samples were reduced about 30 and 40%, respectively, by adding 1.5 wt % nanotubes into PMMA. However, the hardness was improved slightly in high level of MWCNTs content. Moreover, maximum impact strength was seen in the nanocomposite containing 1 wt % MWCNT and adding further nanotubes decreased the impact strength.

It was also shown that injection molding processing conditions played a significant role in the mechanical properties of the nanocomposites, so that changing processing condition can improve the tensile strength and elongation of the nanocomposite by 39 and 42%, respectively. Enhancing holding pressure causes an increase in tensile strength, elongation, impact strength and hardness. Regarding melt temperature, higher tensile strength and the hardness can be obtained by using a low temperature, while higher impact strength were seen in maximum melt temperature. Furthermore, no significant changes in elongation were observed with variations in the melt temperature.

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