Int J Adv Manuf Technol (2017) 88:879–885
DOI 10.1007/s00170-016-8840-9

ORIGINAL ARTICLE

Experimental and modeling investigation on machined surfaces of HDPE-MWCNT polymer nanocomposite

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Received: 6 October 2015 / Accepted: 25 April 2016 / Published online: 2 May 2016

Abstract This study investigates end-milled surfaces of HDPE-MWCNT polymer nanocomposite. The feed rate and the cutting speed are varied and their effects on the surface roughness are investigated in detail. The relationship between the surface roughness and the processing parameters are investigated by using a response table and a response function. In addition, the relationship is also discussed in terms of the Deborah number which characterizes viscoelastic behavior of polymeric materials.

Keywords Polymer nanocomposites · Machining · Surface roughness · Response analysis · Viscoelasticity

1 Introduction

Polymer-based composite materials have been widely used in many applications due to their high mechanical properties (such as specific stiffness, strength, and toughness) and high resistance in corrosive environments [1]. For example, glass or carbon fibers have been extensively used as fillers in polymer composites for applications in the fields of automobile and aerospace for weight reduction. Recently, nanometer-scale materials such as carbon nano-tube (CNT) and graphene are used as fillers because of their exceptional properties [2, 3].

Most of the polymer composite products are manufactured via molding process such as injection molding, compression molding and extrusion. In the mean time, the polymer composites often need machining processes like drilling, cutting and trimming to be fabricated to the final product. In contrast to metallic materials, however, not much has been investigated regarding the machining of the polymer composites [4].

Properties of the machined surface of polymer composites are determined by the processing conditions (such as cutting speed, feed rate, and depth-of-cut) and material properties of the matrix and fillers [5–10]. In addition, the filler orientation also is an important factor affecting the surface finish [11]. Some recent works are briefly introduced in the following.

Rahman et al. [5] has investigated machinability of short- and long-carbon fiber reinforced polymers. They used different kinds of tools, and not only the surface finish but also the tool wear and cutting force are measured for different conditions of cutting speed and depth-of-cut. Eriksen [6] has studied the effect of processing conditions on the surface roughness of short-fiber-reinforced plastic. According to the results, the roughness increases with the feed rate while the effect of the cutting speed is not much significant. The effect of fiber orientation was almost negligible in this study, which, however, needs further investigations as authors had mentioned. Davim et al. [7, 9] compared turning of neat and reinforced plastics in terms of cutting force, feed force, surface roughness, and so on. Similar to the previous works, the surface roughness generally increases with the feed rate. Interestingly, however, the effect was found to be much smaller in the case of the reinforced plastic.

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In addition to those experimental studies, there have been modeling investigation to describe the relationship between the surface roughness and the processing conditions [10–13]. For example, Feng and Wang [12] has developed an empirical model by means of nonlinear regression analysis. Palanikumar [11] introduced a response function where the roughness is expressed as a second-order polynomial of the processing parameters. Razfar et al. [13] used neural network theory to find an optimal processing condition for minimization of the surface roughness.

As far as the machining of polymer nanocomposites is concerned, there are only few investigations which are conducted recently [4, 14]. According to Farshbaf Zinati et al. [4, 14], the fraction of the nano fillers and the spindle speed do not have a significant effect on the surface roughness, while the feed rate has most significant effect.

In the present study, we investigate the end-milled surfaces of concentrated polymer nanocomposite. Effects of processing conditions on the surface roughness are studied based on a response analysis and a response function. Particularly, we define a characteristic number for the machining process of the polymeric material, which is useful to understand the relationship between the surface roughness and the processing condition.

2 Experimental

2.1 Polymer nanocomposite

By using a conventional twin-screw extruder, MWCNTs (average length of 10 μm and outer diameter of 10 ∼ 30 nm) are compounded with HDPE matrix at the mass fraction of 20 wt%. This mass fraction is selected to obtain the thermal conductivity of around 1.0 W/mK for our specific target product. The nanocomposite has tensile strength of 42 MPa and elastic modulus of 1.43 GPa. Ductility of the nanocomposite, on the other hand, is significantly reduced at this high fraction of MWCNTs.

The nanocomposite extrudates are then compression molded to fabricate a specimen which is a plate having a thickness of 1 mm. It should be noted that, if one uses injection molding process to produce specimens, fillers can align along particular directions due to a high strain rate, which results in an anisotropic orientation state of fillers in the specimen [15]. In the compression molding process, however, the strain rate of the material deformation is much lower than that of injection molding process, thus the orientation behavior of fillers is much reduced. In this study, the specimens are fabricated by the compression molding process to avoid anisotropic orientation of MWCNTs. Figure 1 shows dispersion of MWCNTs in so fabricated specimen. One can observe that the MWCNTs are randomly oriented.

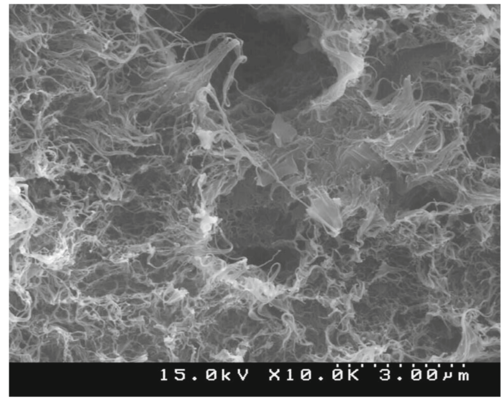


Fig. 1 SEM micrograph of MWCNTs dispersion in HDPE matrix

2.2 Machining

The surfaces of specimens are end-milled by a computer numerical control (CNC) milling machine. The tool (HES4040XLT, TaeguTec) has four edges and the diameter is 4 mm.

As noted by previous works [10, 16], the depth of cut, particularly in the range of micrometer scale, will have only minor effect on the surface roughness compared to the effects of feed rate and cutting speed. In this study, the effects of feed rate and cutting speed on the surface roughness will be investigated, while depth of cut is fixed at 0.3 mm. Particularly, the processing condition of the present study is selected such that one can achieve surface roughness of less than 1 μm for a precision manufacturing of micrometer-sized geometries. In this regard, the feed rate is varied in the range of 0.01 to 0.07 mm/rev which is almost one order lower than conventional processing condition [16, 17]. In the mean time, the tool temperature can reach up to 300 °C when machining common polymer composites with the cutting speed of around 200 m/min [18, 19]. To avoid any thermal damage of the polymer, the cutting speed is varied from 30 to 190 m/min in this study.

2.3 Roughness measurement

Surface roughness of the machined surface is measured by a non-contact 3D surface profiler (Nanoview, NanoSystem). For each specimen, surface roughnesses of three locations are measured, and the average values are used.

3 Results and discussion

3.1 Response analysis

In order to compare the effects of feed rate and cutting speed, a response table is constructed as shown in Table 1

Table 1 Response table of surface roughness

Roughness [nm]	A		B		AB	
	−1	1	−1	1	−1	1
189.41	189.41		189.41			189.41
856.67	856.67			856.67	856.67	
268.07		268.07	268.07		268.07	
643.33		643.33		643.33		643.33
Average	523.04	455.7	228.74	750	562.37	416.37
Effect	−67.34		521.126		−146	

[10, 11]. The processing parameter A denotes the cutting speed and B denotes the feed rate. A of −1 and 1 indicate 30 and 190 m/min, respectively, and B of −1 and 1 indicate 0.01 and 0.07 mm/rev, respectively. Four experiments are carried out, in other words, (A,B) = (−1, −1), (−1, 1), (1, −1) and (1,1), and the roughness of each specimen is measured for response analysis.

According to the response table, it is found that the effect index of B (the feed rate) is much larger than that of A (the cutting speed). In addition, the effect index of A has a negative value, which indicates that the effect of A has a different tendency depending on B. As a result, the effect index of AB is larger than that of A.

For more detailed investigation on the relationship between roughness and the processing condition, more experiments are carried out. The feed rates are 0.01, 0.02, 0.03, 0.04, 0.05, and 0.07 mm/rev, and the cutting speeds are 30, 70, 110, 150, and 190 m/min. Figures 2, 3, and 4 show overall data of the surface roughness obtained experimentally.

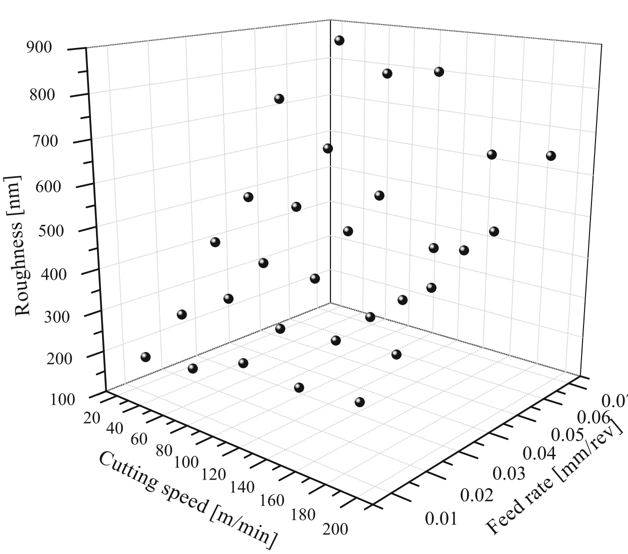


Fig. 2 Three-dimensional plot of surface roughness data

Generally, the roughness increases with the feed rate as one can expect from the large effect index in the response table. This phenomenon has been reported in many previous works [6, 7, 9–11, 17]. In Fig. 3a, the increasing slope of

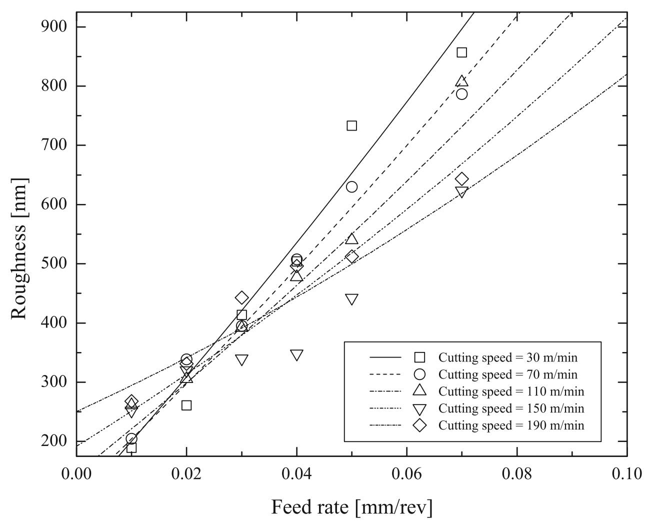


Fig. 3 Surface roughness data (*symbols*) and fitted model (*curves*)

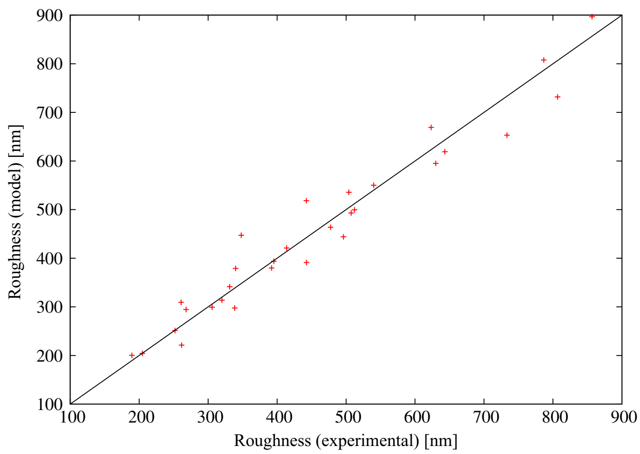


Fig. 4 Correlation between experimental data and fitted model

the roughness decreases as the cutting speed increases. The effect of cutting speed, on the other hand, is significantly dependent on the feed rate (Fig. 3b). Differently from the feed rate effect, the roughness is not monotonically changing with the cutting speed. When the feed rate is larger than 0.03 mm/rev, the roughness decreases as the cutting speed increases. On the other hand, for low feed rate less than 0.03 mm/rev, the roughness slightly increases with the cutting speed. Similar results have been reported previously [20]. Fundamental background for these complex relationship between the roughness and the processing conditions would be due to a viscoelasticity of the polymer [20], which is briefly discussed as follows.

Polymeric materials basically has a viscoelastic property due to their long-chain molecular structure [21]. One non-dimensional parameter characterizing this viscoelastic behavior is the Deborah number which is defined as follows

$$\mathrm{De} = \frac{\lambda}{\tau} \tag{1}$$

where λ is the relaxation time scale of the material and τ is the processing time scale (or deformation time scale) [21]. When the Deborah number is high, the polymeric material behaves like an elastic solid, while the material behavior becomes similar to a viscous liquid when the Deborah number is low.

One may write the processing time scale τ as follows

$$\tau = \frac{D}{v} \tag{2}$$

where D is the tool diameter and v is the cutting velocity. In the mean time, the relaxation time scale λ is dependent on the temperature, and one simple model for this relationship is an Arrhenius form written as follows

$$\lambda = \lambda_0 \exp(T_0/T) \tag{3}$$

where T is the temperature and λ_0 is the reference value at the reference temperature T_0.

In the machining process, the cutting temperature T is significantly affected by the cutting velocity, of which relationship can be written as [16, 22]

$$T = Kv^m \tag{4}$$

where K and m are parameters depending on the cutting condition.

Therefore, the Deborah number can be written as follows

$$\mathrm{De} = \frac{\lambda_0 v}{D} \exp[T_0/(Kv^m)] \tag{5}$$

from which one can find that De has a non-linear relationship with respect to the cutting velocity. This indicates that the physical property of the material is dependent on the cutting speed, while the feed rate would not have a significant effect on the material behavior. As the cutting speed increases, the Deborah number will first decrease and then increase monotonically.

Although a quantitative analysis requires specific value of each parameter and further analysis, Eq. 5 reflects that the material behavior is affected by the cutting speed. Therefore, the cutting speed effect on the roughness can be rather complicated than the effect of the feed rate in particular range of the processing conditions, even though its effect on the roughness is not as much as that of the feed rate.

More details about the relationship between the roughness and the processing conditions will be discussed in the following section with the help of a response function.

3.2 Response function

The relationship between the response (surface roughness, R_a) and the processing parameters (cutting speed and feed rate) can be written as follows [11]

$$R_a = a_0 + a_1 v + a_2 f + a_3 v f + a_4 v^2 + a_5 f^2 \tag{6}$$

where a_i, $(i = 1, 2, \cdots, 5)$ are response function parameters, v is the cutting speed, and f is the feed rate. The response function parameters are obtained by a least square fitting of the function to the experimental data, and the values are $a_0 = 88.36$, $a_1 = 0.077$, $a_2 = 11619.15$, $a_3 = -38.73$, $a_4 = 0.0040$, and $a_5 = 14373.66$ respectively. Considering that the characteristic values of cutting velocity and feed rate (namely, $\bar{v}$ and $\bar{f}$) are 190 m/min and 0.07 mm/rev, respectively, one can compare contribution of each term in Eq. 6. According to this analysis, $a_1\bar{v}$ and $a_5\bar{f}^2$ are relatively small compared to the others. Therefore, the roughness is almost linear to the feed rate, while it is almost quadratic to the cutting speed. It might be also mentioned that $a_3\bar{v}\bar{f}$ reflecting the combinational effects of the feed rate and the cutting speed is larger than $a_1\bar{v}$ and $a_4\bar{v}^2$, which means that the effect of cutting speed is significantly dependent on the feed rate. In the present processing condition, effect of the cutting speed becomes more significant as the feed rate increases.

The response function and experimental data are compared in Fig. 3. As mentioned before, the roughness changes significantly as the feed rate changes, while the cutting speed has relatively small effect on the roughness. As shown in Fig. 3a, the roughness increases almost linearly with the feed rate. In contrast, the quadratic nature of the cutting speed effect is observed in Fig. 3b.

The correlation between experimental data and response function is shown in Fig. 4. Overall experimental data can be well predicted by the response function.

3.3 Surface micrographs

Figure 5 shows surface micrographs obtained by 3D surface profiler. The tool had been translated from the left to the right. The feed mark becomes clearly visible as the feed rate is increased from 0.01 mm/rev (Fig. 5a, b) to 0.05 mm/rev (Fig. 5c, d). When the feed rate is 0.05 mm/rev, the feed mark becomes less pronounced as the cutting speed increases. On the other hand, when the feed rate is 0.01 mm/rev, the cutting speed effect cannot be clearly identified in these micrographs, thus more details are discussed with SEM micrographs in the followings.

Figure 6 shows SEM micrographs of the machined surfaces when the feed rate is 0.01 mm/rev and the cutting speed is varied. In Fig. 6a, one can find that the polymer is significantly stretched along a particular direction, which indicates large shear deformation at the surface as the tool edge cuts the material. When cutting speed is increased, on the other hand, as shown in Fig. 6b, the shear deformation is less noticeable and the surface is rather irregular. Consequently, the surface roughness slightly increases as the cutting speed increases in Fig. 3b. As mentioned previously, this could be an indicative of the viscoelastic behavior.

MWCNTs could not be identified from the SEM micrographs, which would be due to strong adhesion between HDPE and MWCNTs and a small length scale of MWCNTs. Therefore, as far as the surface roughness is concerned, the feed mark would be the main factor. However, the nanoscale textures observed in Fig. 6 could be related to the MWCNTs. In the present work, this relationship could not be explicitly clarified because visualization of both MWCNTs and surface texture is technically difficult

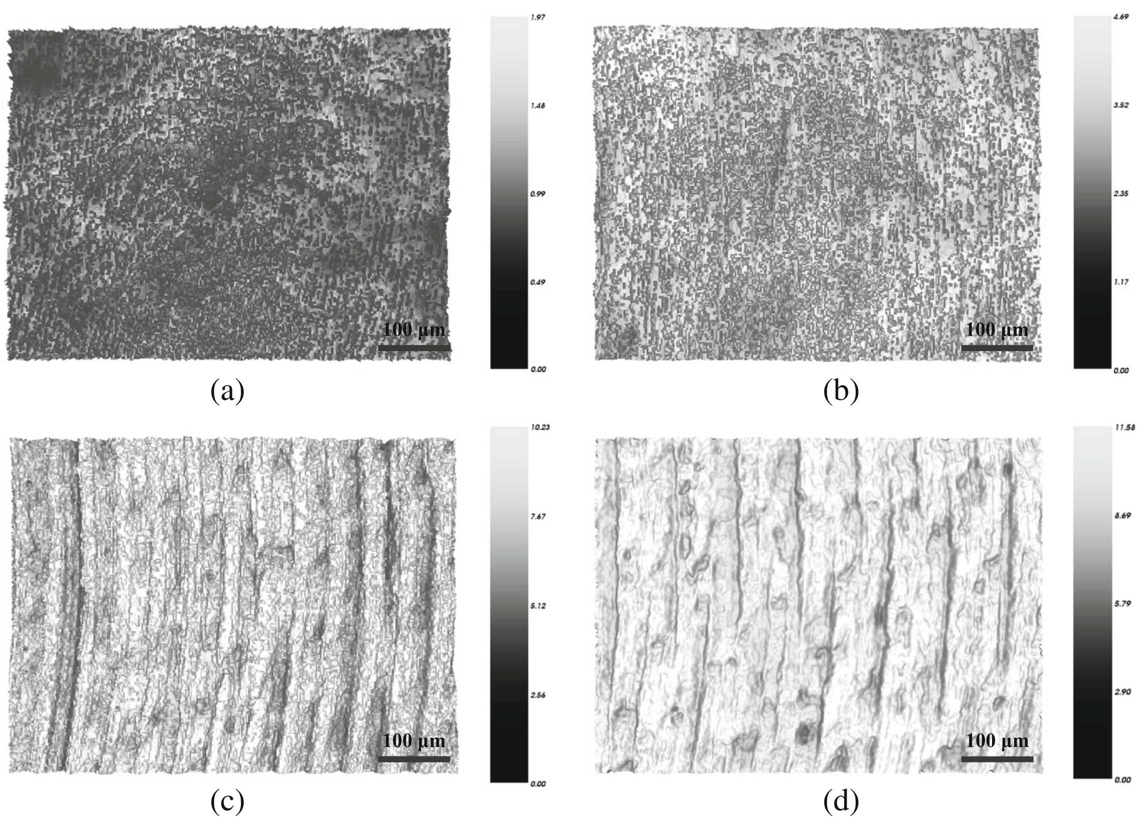
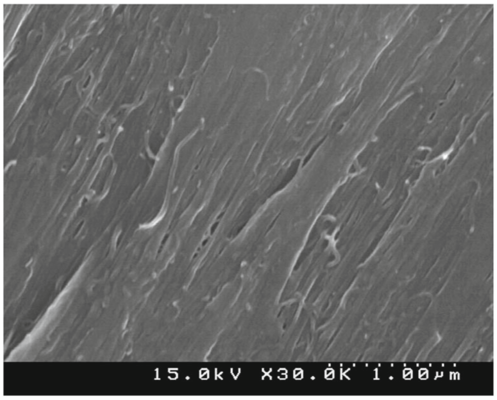
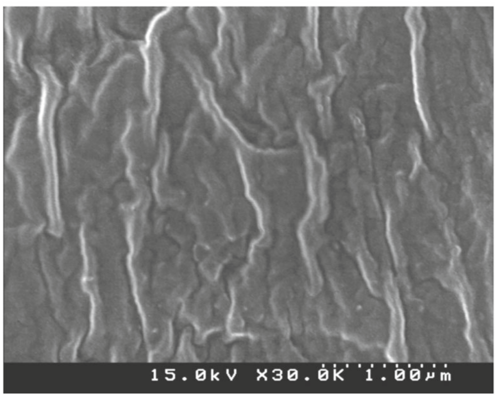


Fig. 5 Surface micrographs of machined surfaces at **a** feed rate of 0.01 mm/rev and cutting speed of 30 m/min, **b** feed rate of 0.01 mm/rev and cutting speed of 190 m/min, **c** feed rate of 0.05 mm/rev and cutting speed of 30 m/min, and **d** feed rate of 0.05 mm/rev and cutting speed of 190 m/min



(a)



(b)

Fig. 6 SEM micrograph of a machined surface at **a** feed rate of 0.01 mm/rev and cutting speed of 30 m/min and **b** feed rate of 0.01 mm/rev and cutting speed of 190 m/min

issue. It might be mentioned that, in conventional polymer composites which have microscale fillers such as glass fibers inside, the roughness can be significantly affected by protruding fillers.

4 Conclusions

In the present study, we have studied the surface characteristics of end-milled HDPE-MWCNT polymer nanocomposite. MWCNTs are mixed with HDPE at 20 wt%, which is then compression molded to fabricate specimens. The feed rate and the cutting speed are varied and their effects on the surface roughness are investigated in detail. The processing condition is selected such that the surface roughness is less than micrometer scale. A response table and a response function are employed to analyze the relationship between the surface roughness and the processing parameters.

The experimental results can be summarized as follows.

- In the present HDPE-MWCNT nanocomposite, the feed rate has more significant effect on the surface roughness than the cutting speed does.
- The surface roughness changes almost linearly with the feed rate, while it is almost quadratic to the cutting speed.
- The complicated relationship between the surface roughness and the cutting speed is discussed in terms of the viscoelastic nature of the polymeric material.
- The feed mark is the main factor determining the surface roughness.
- Nanometer-scale textures are observed on the machined surface, which is due to significant shear deformations during the feeding.

Acknowledgments This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (No. 2015R1C1A1A02036960). This work was conducted under the framework of Research and Development Program of the Korea Institute of Energy Research (KIER) (B5-2417-01).

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