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Effects of machining on tribological behavior of ultra high molecular weight polyethylene (UHMWPE) under dry reciprocating sliding

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Abstract

This paper presents a study of the machining effect on tribological properties of ultra high molecular weight polyethylene (UHMWPE) in terms of coefficient of friction and wear factor under dry reciprocating sliding conditions. Machining parameters include cutting speed, feed rate and depth of cut. Polymeric structure of the semicrystalline polymer was characterized using differential scanning calorimetry (DSC). Changes in polymeric structure and surface texture caused by machining were related to the tribological behavior of machined UHMWPE. The average coefficient of friction increased quickly in the first 60 s. Then the coefficient of friction increased very slowly and reached a steady state. The initial average coefficient of friction was in the range from 0.12 to 0.15. After 1 h of dry sliding, the average coefficient of friction was in the range from 0.17 to 0.23. No significant correlations were found between depth of cut and coefficient of friction, or between cutting speed and coefficient of friction. However, coefficient of friction decreased as cutting speed increased when the same ratio of cutting speed to tool feed rate was maintained. Increase in cutting speed caused more damage on the subsurface structure of machined UHMWPE. Wear factor decreased as cutting speed increased if tool feed rate was kept unchanged. Wear factor increased as cutting speed increased when the ratio of cutting speed to tool feed rate was kept constant. There was an optimum depth of cut for the best surface roughness and wear resistance, which was about 0.127 mm under the studied condition. Optical microscopy and variable pressure scanning electron microscopy analysis showed severe plastic deformation and ploughing as the main wear mechanisms.

Keywords: Ultra high molecular weight polyethylene; Dry sliding; Cutting speed; Coefficient of friction

1. Introduction

There has been considerable interest in the study of wear behavior of ultra high molecular weight polyethylene (UHMWPE) [1–5]. Most UHMWPE bearings are manufactured by machining from ram-extruded stocks. The subsurface structure and properties of machined UHMWPE play an important role in the initial wear of the material. However, no systematic investigation of machining effects on polymeric structure and tribological behavior of UHMWPE is available.

Cooper et al. [6] studied the effect of a transfer film on the wear of lubricated UHMWPE. The authors stated that different wear rates were related to the formation of a UHMWPE transfer film on the counter surface of stainless steel. The formation of a transfer film changed the surface roughness of the counterface, which affected the wear of UHMWPE. Full simulation of joint forces and motions in hip joint simulators is extremely complex [7] and the measurement of the effects of contact stresses on wear has not been very successful. Using simplified wear tests, studies by Rose et al. [8] and McKellop et al. [9] have shown that wear rate increased exponentially with load or contact stress. In another study by Barbour et al. [10], a polymeric pin-on-plate system was used with serum lubrication at a lower stress range (3.45 to 6.90 MPa) and the wear factor was found to be constant. The polymer pin on plate test configuration was believed to be a more representative simulation of hip joints where the contact area is restricted to one part of the UHMWPE acetabular cup. The metal pin on polymer plate configuration was considered more representative of knees [10].

Counterface topography is another important factor that controls the wear rate of UHMWPE. Weightman and Light [11] studied the effect of surface finish of alumina and stainless steel on the wear rate of UHMWPE. The results indicated that the wear rate of UHMWPE fell as the surface finish of both alumina and stainless steel improved

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down to 0.015 μm R_a. They also investigated the effect of surface roughness on coefficient of friction. The initial and steady-state friction curves were approximately parallel for roughnesses larger than 0.05 μm R_a. Besong et al. [12] investigated the combined effect of damage to polished femoral heads, as well as oxidation and aging after gamma sterilization on wear resistance of UHMWPE. The wear rate of UHMWPE sterilized by gamma irradiation in air was shown to increase significantly with aging time on the shelf for all counterface roughness conditions. The wear rate of all materials increased markedly as the conterface roughness increased. The combined effect of aging and surface damaging had a dramatic effect (as high as 2000-fold increase) on wear rate. Lancaster et al. [13] reported that the wear factor was proportional to the counterface roughness to a power greater than one.

Rostoker et al. [14] noted that at least four mechanisms were consistent with the appearance of the wear surface. By considering additional evidence, Nusbaum et al. [15] eliminated all but two, adhesive and abrasive wear. McKellop et al. [16] compared the microscopic morphology of worn polyethylene surfaces with that of the associated polyethylene particles for acetabular cups tested in a wear simulator and worn in vivo. They reported that the morphology of worn polyethylene from in vitro and in vivo wear included nodules and fibrils, which is consistent with adhesive, abrasive and micro-fatigue wear mechanisms.

Structural variables such as molecular weight, molecular weight distribution, cross-linking and fusion defects (shape, size and density) affect the wear behavior of UHMWPE. Rose et al. [8] studied the wear of UHMWPE in bovine serum and reported that an increased molecular weight of UHMWPE led to improvement of its wear behavior. Nusbaum et al. [15] concluded in agreement with the results from total joint simulations and clinical retrievals, that the most important wear processes depend on fusion defects and other structural features of the UHMWPE.

Effects of machining on polymeric structure and tribological properties of UHMWPE were studied in this paper. Machining variables include cutting speed, tool feed rate and depth of cut. Tribological characteristics were assessed in terms of coefficient of friction and wear factor under dry reciprocating sliding conditions. Molecular structure of the subsurface layer was studied with differential scanning calorimetry (DSC) analysis of machined UHMWPE chips. Machining effects on tribological properties of machined UHMWPE were correlated with polymeric degradation and change in surface texture due to machining.

2. Experimental details

2.1. Reciprocating friction and wear test

Dry sliding tests were carried out on a pin on plate reciprocating wear testing machine. The pin was loaded at 10.63 N (1085 g). The nominal contact surface was an ellipse with a long axis of 1.5 mm and a short axis of 0.85 mm. The nominal contact pressure was about 10.6 MPa. The peak sliding velocity was 0.135 m s^{-1} with a stroke length of 25.7 mm. The reciprocating frequency was 100 cpm. Coefficient of friction was monitored by two load cells. Signals from the two load cells were recorded through two channels using a high speed data acquisition system controlled by a LabVIEW virtual instrument (VI) program. The data acquisition rate was 2000 scans s^{-1} with an average of 50 points used to smooth the data.

2.2. Specimen preparation

A turret mill with a rough cutter or a final cutter of two-lipped type was used to machine the UHMWPE. Before machining, the mill was completely cleaned to avoid any contamination of the specimen during machining. The cutting speed was calibrated using a digital tachometer before each cut. Tool feed rate and depth of cut were also calibrated before each cut.

The machining procedure was divided into rough cut and final cut. All rough cuts had identical parameters with a cutting speed of 3.49 m s^{-1} (3500 rpm), a tool feed rate of 14.8 mm s^{-1} and a depth of cut of 1.27 mm. To study the effect of cutting speed, five different cutting speeds of 0.499, 1.50, 2.49, 3.49, and 4.49 m s^{-1} (500, 1500, 2500, 3500 and 4500 rpm) were used. Tool feed rate was kept at 8.47 mm s^{-1} (20 in. min^{-1}) and depth of cut at 0.203 mm (0.008 in.).

To study the effect of depth of cut, cutting speed and tool feed rate were kept at 4.49 m s^{-1} (4500 rpm) and 8.47 mm s^{-1}, respectively. The depths of cut were 0.0508, 0.127, 0.203, 0.508 and 1.02 mm, respectively.

To factor out the effect of surface finish due to machining, an experiment was designed to maintain a constant ratio of cutting speed to tool feed rate while the depth of cut was kept at 0.203 mm (0.008 in.). The ratio was 0.499 m s^{-1} (500 rpm)/1.058 mm s^{-1} (2.5 in. min^{-1}).

Metal pins were cut from artificial femoral components from the portion designed to make contact with UHMWPE knee bearings. Before wear tests, metal pins and UHMWPE samples were cleaned with an ultrasonic cleaner in deionized water for 5 min and then in isopropyl alcohol for 10 min.

2.3. Surface analysis

The surface profiles of metal pins and UHMWPE plates were measured before and after the sliding test. Depths of wear tracks on the UHMWPE plates after wear testing were used to calculate the volumetric loss of material due to dry sliding. These measurements were performed using a Surfcom 120A surface texture measuring system controlled by Profile View software. The system has a light force transducer suitable for polymer surface evaluation. Measuring parameters include a filter cutoff of 0.8 mm, an evaluation length of 4.0 mm, traverse length of 4.87 mm and vertical resolution of 0.0009 μm.

Wear surface was observed using optical microscopy and variable pressure scanning electron microscopy (VP-SEM). One of the major advantages of using variable pressure scanning electron microscopy is that no surface coating is necessary for the polymeric sample observed in the back-scattered electron mode. In this way, the artifacts of coating are eliminated.

2.4. Differential scanning calorimetry (DSC) analysis

Differential scanning calorimetry (DSC) analysis was performed with a Du Pont 2000 differential scanning calorimeter. Machined UHMWPE chips were used as samples for the analysis. The chips were pressed into a disk using an UHMWPE die under the pressure of 17.4 MPa for 4 s. Then, DSC samples were cut from the disk. The sample mass was in the range from 5 to 10 mg. The heating rate for DSC analysis was 10°C min^{-1} and a heating range from room temperature to 170°C. DSC analysis of chips in the same group was performed in the same calibration period within 3 days after machining.

3. Results and discussions

3.1. Coefficient of friction

Fig. 1 shows a typical variation in coefficient of friction recorded for a metal pin on UHMWPE plate reciprocating dry sliding test. The positive coefficient of friction was recorded in the first half cycle of the reciprocating sliding process. The negative value was recorded in another half cycle of the reciprocating sliding process. The curve is symmetrical, representing the nature of reciprocal sliding.

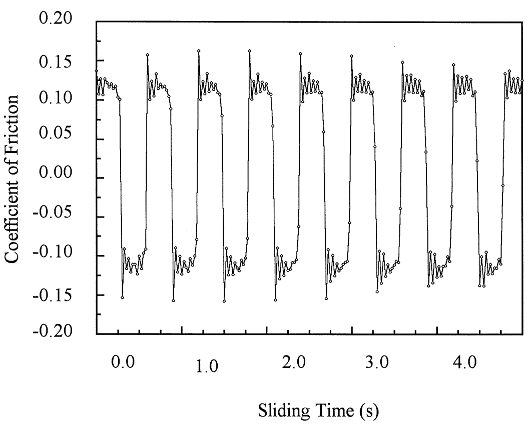

Fig. 1. Variation in coefficient of friction in the initial 5 s of reciprocal dry sliding test of metal pin on machined UHMWPE plate. Machining conditions include a cutting speed of 3.49 m s^{-1} (3500 rpm), tool feed rate of 7.4 mm s^{-1} and depth of cut of 0.203 mm.

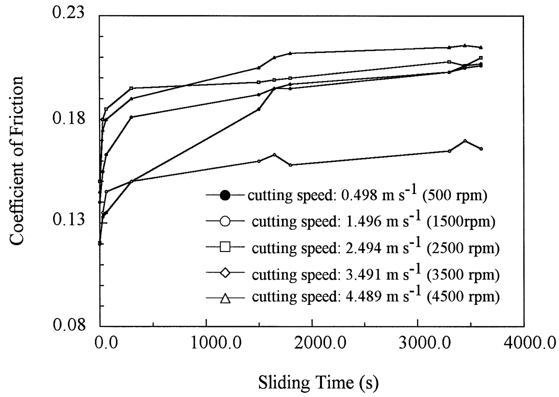

Fig. 2. Average coefficient of friction for metal pin on UHMWPE plate machined with different cutting speeds in a reciprocal dry sliding test. Other machining conditions included tool feed rate of 8.47 mm s^{-1} and depth of cut of 0.203 mm.

The coefficient of friction varied in each half cycle. It was highest at the beginning of each half cycle while it became lowest at the end of each half cycle. It is believed that a transition from static to dynamic friction happened at the beginning of each half cycle, while a dynamic to static friction transition occurred at the end of each half cycle.

Fig. 2 shows the variation in average coefficient of friction with sliding time for a metal pin on UHMWPE plate machined at various cutting speeds. The tool feed rate was 8.47 m s^{-1} and depth of cut was 0.203 mm. Coefficients of friction were in the range from 0.12 to 0.15 at the very beginning of tests. In the initial 60 s, the coefficient of friction increased very quickly. Then, the coefficient of friction increased slowly before it reached a steady state. It could also be seen that no significant correlation was found between cutting speed and coefficient of friction.

Fig. 3 summarizes the effect of depth of cut on coefficient of friction. The cutting speed and tool feed rate were at 4.49 and 8.47 mm s^{-1}, respectively. Average coefficients of friction were measured immediately after 1 h of

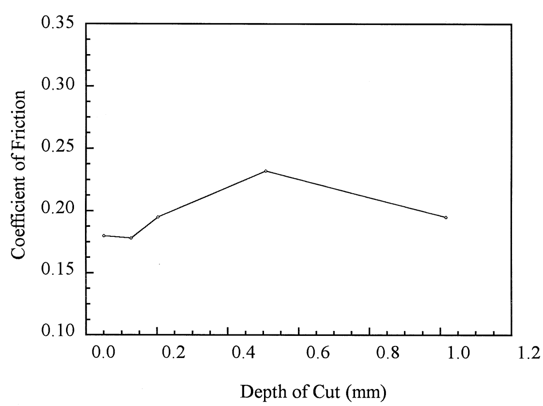

Fig. 3. Effect of depth of cut on the average coefficient of friction of metal pin on machined UHMWPE plate.

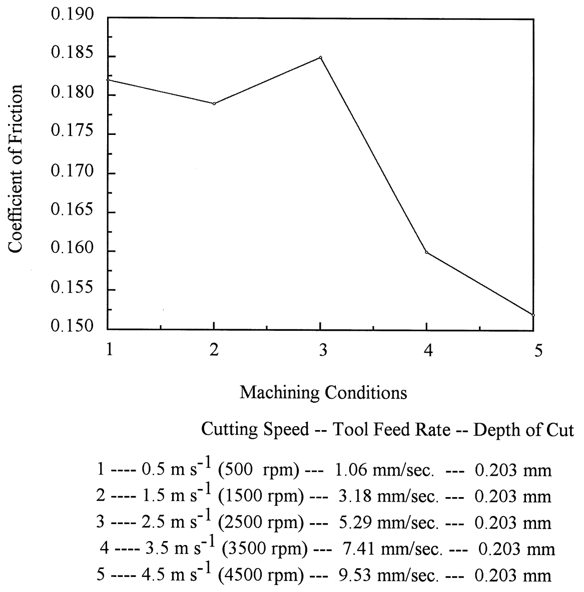

Fig. 4. Variation in coefficient of friction with cutting speed or tool feed rate with a constant ratio of cutting speed to tool feed rate.

sliding. It is noted that there was no significant correlation between depth of cut and coefficient of friction.

Fig. 4 shows the variation in coefficient of friction with cutting speed or tool feed rate when identical ratio of cutting speed to tool feed rate was maintained. The depth of cut was kept as 0.203 mm in this experiment. Coefficient of friction was also measured immediately after 1 h of sliding. It is noted that the coefficient of friction decreased as the cutting speed or tool feed rate increased.

3.2. Machining effects on wear of UHMWPE

Fig. 5 shows the variation in wear factor of machined UHMWPE as a function of cutting speed. It could be seen that the wear factor decreased as cutting speed increased while holding tool feed rate and depth of cut at 8.47 mm s^{-1} and 0.203 mm, respectively. In other words, as cutting speed increased, the wear resistance of machined UHMPWE was improved. Fig. 5 also shows the onset melting temperature as a function of cutting speed. As the cutting speed increased, the onset melting temperature decreased as well. The decrease in onset melting temperature of the polymer is related to subsurface damage or decrease in crystallinity [17]. Thus, as the cutting speed increased, more severe damage occurred in the subsurface layer.

The wear of the subsurface layer of machined UHMWPE can be explained by two major factors: the structure of the subsurface layer and the surface texture after machining. Fig. 6 illustrates the model of surface texture created by a two-lipped milling cutter. The surface texture consisted of peaks formed by forward cut and backward cutting. The base angle equals the end cutting edge concavity angle of the milling cutter. The distance between two neighboring peaks equals the tool feed rate divided by twice of cutting speed. If the ratio of cutting speed to tool feed rate were doubled, the distance between two neighboring peaks would be reduced to half of the initial distance. The surface texture measured after machining showed agreement with the model in Fig. 6.

As shown in Fig. 5, more mechanical degradation occurred at higher cutting speed. Thus, higher cutting speed would lead to a higher wear factor due to structural damage. However, higher cutting speed also results in shorter peak intervals as shown in Fig. 6. As a result, the real contact area between metal pin and UHMWPE plate was increased. This caused the contact pressure or the microscopic stress to decrease, which resulted in a lower wear. It is inferred that the wear factor was dominated more by changes in surface texture than by changes in subsurface polymeric structure.

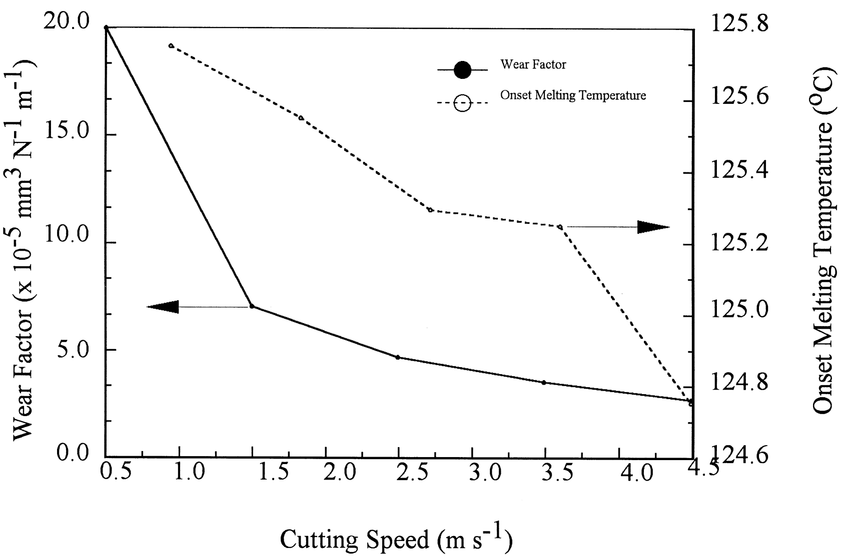

Fig. 5. Effect of cutting speed on wear factor and onset melting temperature of machined UHMWPE.

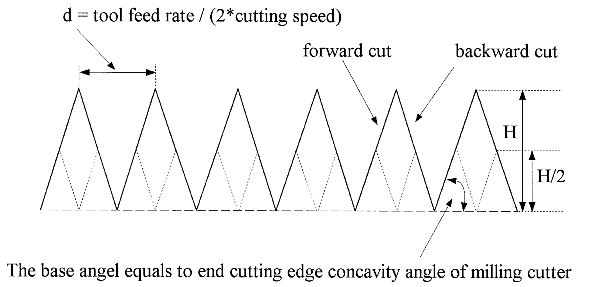

Fig. 6. A model for surface texture formation when a two-lipped milling cutter is used. If the ratio of cutting speed to tool feed rate is increased twice, the surface roughness will be improved as shown by dashed contour.

Fig. 7 shows variations of wear factor and onset melting temperature of machined UHMWPE with cutting speed or tool feed rate while a constant ratio of cutting speed to tool feed rate was maintained. The wear factor increased with increase in cutting speed while the onset melting temperature decreased with cutting speed. As shown by the model in Fig. 6, the surface texture should be the same when the ratio of cutting speed to tool feed rate was held identical. However, more mechanical degradation occurred as cutting speed increased, as shown by the onset melting temperature. Thus, the change in wear factor was mainly attributed to the polymeric structural change due to machining. In summary, higher cutting speed caused more mechanical degradation, which led to lower wear resistance for machined UHMWPE.

Fig. 8 illustrates the effect of depth of cut on the wear factor and surface roughness of machined UHMPWE. Both the wear factor and surface roughness (R_a) showed

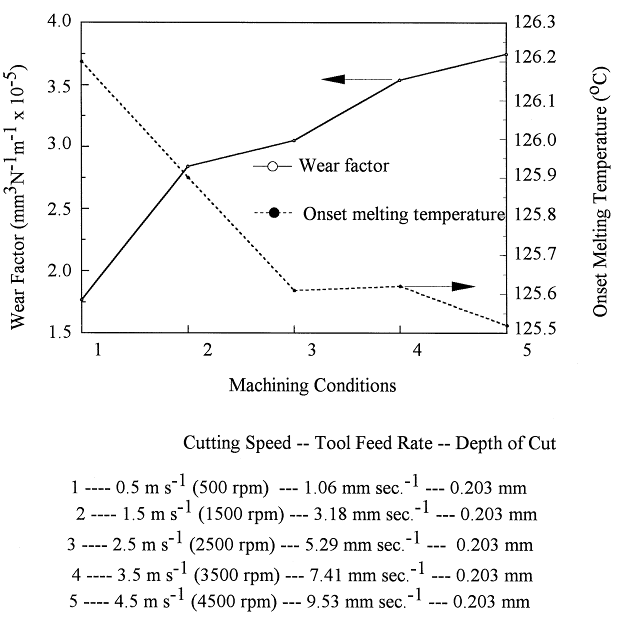

Fig. 7. The variations of wear factor and onset melting temperature of machined UHMWPE with machining conditions kept the same ratio of cutting speed to tool feed rate.

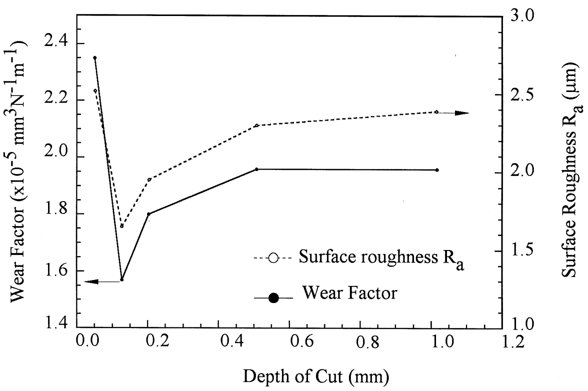

Fig. 8. Effect of depth of cut on wear factor and surface roughness of machined UHMWPE. Cutting speed and tool feed rate were 4.489 and 8.47 mm s^{-1}, respectively.

the same trend as the depth of cut increased. When the depth of cut was less than 0.127 mm, the wear factor and surface roughness (R_a) decreased as depth of cut increased. When the depth of cut was in the range from 0.127 mm to about 0.500 mm, the wear factor and surface roughness (R_a) increased as depth of cut increased. When the depth of cut was larger than 0.5 mm, the wear factor and R_a remained fairly steady as depth of cut increased. It is concluded that better surface finish led to better wear resistance when other conditions were kept the same. There is an optimum depth of cut for the best wear resistance and surface finish of UHMWPE. The optimum value of depth of cut was about 0.127 mm under the conditions studied.

3.3. Study of the wear mechanisms

Variable pressure scanning electron microscopy (VP-SEM) was employed to study the worn surface to understand the wear mechanism governing the tribological behavior of machined UHMWPE. Fig. 9 shows a typical

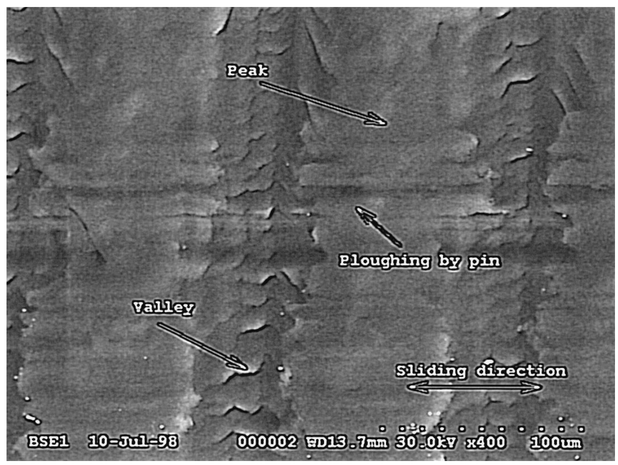

Fig. 9. Variable pressure SEM micrograph of worn surface of UHMWPE. Machining conditions include a cutting speed of 3.99 m s^{-1} (4000 rpm), tool feed rate of 8.47 mm s^{-1} and depth of cut of 0.127 mm (0.005 in.).

VP-SEM micrograph for the surface of UHMWPE machined with a cutting speed of 3.99 m s^{-1} (4000 rpm), tool feed rate of 8.47 mm s^{-1} and depth of cut of 0.127 mm. The specimen has been tested for 1 h under reciprocating dry sliding. There is no surface coating on the surface before observation. It is noted that the main event on the surface was plastic deformation induced by the dry sliding. The asperity peaks were ploughed by the metal pin whereas the valley was not touched.

Optical microscopic observation was also conducted on the sliding track on a UHMWPE plate. Fig. 10 shows the boundary area between the sliding track and the unaffected surface area of UHMWPE machined under the same conditions as Fig. 9. It can be seen that peaks and valleys conform to what has been modeled in Fig. 6. The distance between neighboring asperity peaks was 0.06 mm, which approximately equals to 0.0635 mm calculated by tool feed rate divided by twice the cutting speed. On the sliding track, asperity peaks were flattened by the metal pin. They were also ploughed by the metal pin, which is evidenced by the visible tracks. Valleys can still be identified in the area where there are no ploughed grooves.

Fig. 11 depicts optical micrographs of the central area on the sliding track of a UHMWPE plate machined with a constant ratio of cutting speed to tool feed rate. Fig. 11a had a cutting speed of 1.5 m s^{-1} (1500 rpm) and tool feed rate of 3.18 mm s^{-1}, whereas Fig. 11b had a cutting speed of 4.49 m s^{-1} (4500 rpm) and tool feed rate of 9.53 mm s^{-1}. The depth of cut was 0.203 mm for both cases. The surface topographies on the two surfaces are expected to be comparable due to the fact that both specimens were machined with the same ratio of cutting speed to tool feed rate. Deeply ploughed grooves and some valley area can be seen along the sliding direction in Fig. 11a. However, the surface became much more flat in Fig. 11b than that in Fig. 11a. No deeply ploughed grooves could be seen in Fig. 11b and the surface texture created by machining was almost worn away. In other words, asperity peaks on UHMWPE machined with higher cutting speed or tool feed rate were worn away faster than those machined with lower cutting speed or tool feed rate. This surface feature conforms with what was discussed in Fig. 7 in that higher cutting speed caused more mechanical degradation, which led to lower wear resistance of machined UHMWPE.

Fig. 12 shows optical micrographs of the central area on the sliding track to illustrate the effect of depth of cut on wear behavior. Machining conditions include a cutting speed of 3.99 m s^{-1} (4000 rpm), tool feed rate of 8.47 mm s^{-1}. Fig. 12a is for a depth of cut of 0.127 mm (0.005 in.) whereas Fig. 12b is for a depth of cut of 0.0508 mm (0.002 in.). It can be seen that the peak area in Fig. 12b is wider for UHMWPE machined with a depth of cut of 0.0508 mm than the peak area in Fig. 12a. Deeper plough grooves also can be seen in Fig. 11b than in Fig. 12a. The above facts suggested that UHMWPE machined with a depth of cut of 0.0508 mm had higher stress and more severe wear during dry sliding than that machined with a depth of cut of 0.127 mm. This agrees with the results in Fig. 11 in that

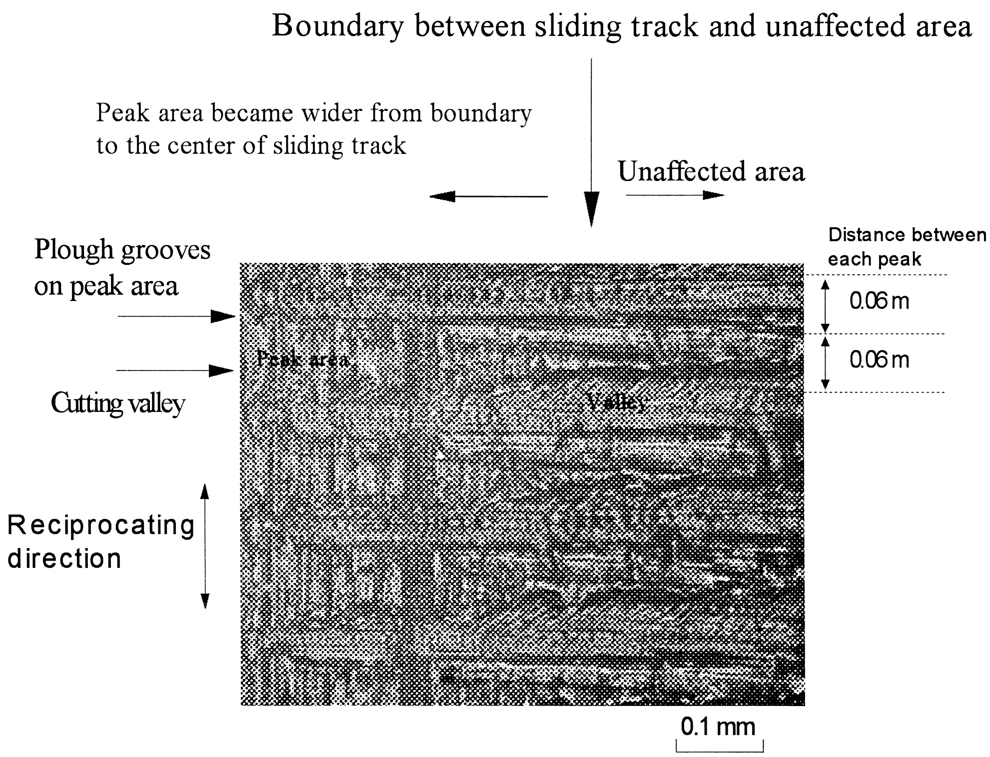

Fig. 10. Optical micrograph showing the boundary area between sliding track and unaffected area on machined UHMWPE block. Machining conditions: cutting speed: 3.99 m s^{-1} (4000 rpm), tool feed rate: 8.47 mm s^{-1} (20 in. min^{-1}) and depth cut: 0.127 mm (0.005 in.).

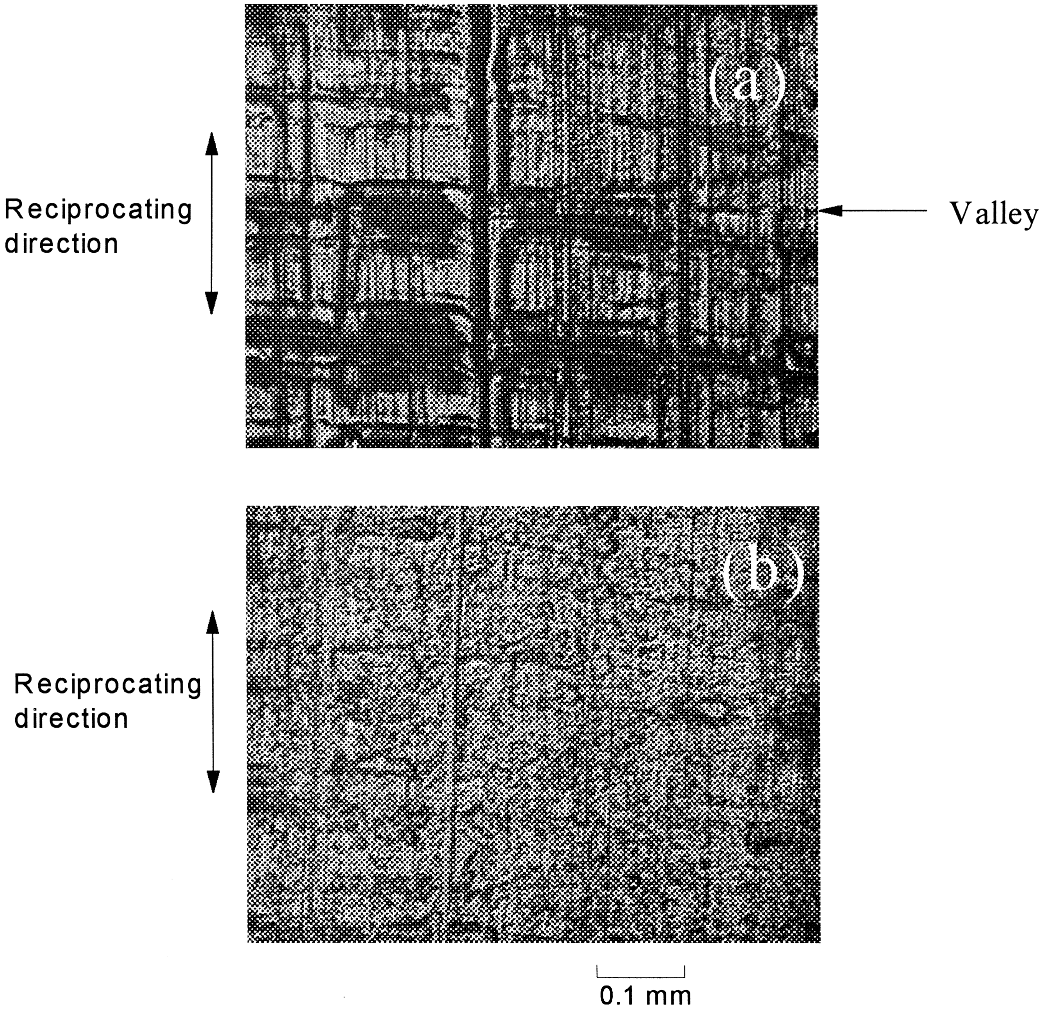

Fig. 11. Optical micrograph in the center of sliding track of UHMPWE plate machined with a constant ratio of cutting speed to tool feed rate. (a) Cutting speed of 1.5 m s^{-1} (1500 rpm) and tool feed rate of 3.18 mm s^{-1}; (b) cutting speed of 4.49 m s^{-1} (4500 rpm) and tool feed rate of 9.53 mm s^{-1}. The depth of cut was 0.203 mm for both cases.

UHMWPE machined using a depth of cut of 0.127 mm had the lowest wear factor.

4. Conclusions

(1) The coefficient of friction of a metal pin on UHMWPE had static and dynamic characteristics during the reciprocal dry sliding. At the beginning of each half cycle, the coefficient of friction was much higher than the average, indicating a static to dynamic transition. At the end of each half cycle, the coefficient of friction was lower than the average, indicating a dynamic to static transition.

(2) The average coefficient of friction increased quickly in the first 60 s. Then, it increased very slowly before it reached a steady state. The initial coefficient of friction was in the range from 0.12 to 0.15. After 1 h of sliding, the coefficient of friction was in the range from 0.17 to 0.23.

(3) No significant correlations were found between depth of cut, cutting speed and coefficient of friction.

(4) Increase in cutting speed damaged the subsurface structure of machined UHMWPE. The wear factor decreased as the cutting speed increased if tool feed rate was unchanged. The wear factor increased as cutting speed increased when the ratio of cutting speed to tool feed rate was kept the same.

(5) There was an optimum depth of cut for the best surface roughness, which led to the lowest wear factor. The optimum value of depth of cut was about 0.127 mm under the conditions studied.

(6) Surface analysis showed that plastic deformation and ploughing on the surface of machined UHMWPE were the main wear mechanisms.

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