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Fabrication of optical surfaces on polymethyl methacrylate by ultra-precision diamond turning

Makitoshi Shimizu[1], Jiwang Yan[1,#]

[1] Department of mechanical Engineering, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama, 223-8522, Japan
Corresponding Author / Email: yan@mech.keio.ac.jp, TEL: +81-45-566-1485, FAX: +81-45-566-1495

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In this study, we attempted to investigate the fundamental cutting mechanisms of PMMA in ultra-precision diamond turning. First, the effect of tool feed rate on material removal behavior was investigated. The flow-type chips, which indicate ductile mode cutting, were observed at all feed rates. However, chips with uneven widths occurred at low feed rates, indicating that machining became unstable. The relationship between surface roughness and feed rate was also explored by measuring surface roughness using a white-light interferometer. It was found that the surface roughness worsened as the feed rate decreased, which showed an opposite trend to the results of glass and metals cutting. Furthermore, the effect of cutting speed on surface formation mechanism was investigated. At a low feed rate (1 µm/rev), the surface finish was improved with decreasing the cutting speed. In contrast, when the feed rate was high (10 µm/rev), surface quality became worse as the cutting speed decreased. By observations of the machined surface and chips at different cutting speeds and feed rates, it was found that the thermoplasticity and brittleness of PMMA are two key factors that affect the machining characteristics. By optimizing the cutting parameters, a surface roughness of lower than 5 nm Sa was achieved, which meets the requirement of optical lenses. These results help to understand the ultra-preicison cutting characteristics of PMMA and are expected to contribute to the fast fabrication of high-quality optical polymer lenses.

1. Introduction

Recently, demands for polymer materials with lightweight and high transmittance have been increasing for producing optical components. One of the most widely used polymers for the manufacture of optical components is polymethyl methacrylate (PMMA), which has outstanding optical performance among various polymers due to its low light dispersion and excellent transmittance, which is comparable to that of optical glass[1,2]. Currently, optical lenses made of PMMA are mainly mass-produced by injection molding. However, the molding process requires the use of high-precision molds, resulting in high production costs. In addition, optical lens production is now shifting toward high-mix, low-volume production, and thus efficient and flexible production methods are expected. The molding process is not suitable for small-lot production, especially, prototyping. As an alternative, ultra-precision diamond turning has been proposed as a promising solution, which enables to directly machine complex shapes with high precision on polymers. In addition, since no molds are required, it facilitates high-mix, low-volume production, and demand is increasing, especially in the product prototype stage.

Polymer materials have very different mechanical and physical properties to optical glass and metals, which would cause unique machining characteristics. Moreover, the machining characteristics of various types of polymers are also different. Therefore, research on the machinability of polymers has been conducted. Xiao et al.[3] reported that increasing cutting speed causes temperature rising and softening of polyethylene, which enables ductile mode cutting. The transition to brittle mode cutting occurs when further increasing cutting speed and strain rate of polymers. Also, Carr et al.[4] showed that the viscoelastic properties of polymers affect the surface roughness. Since viscoelastic properties are dependent on cutting time and temperature, they showed that the material softens with rising temperature as the cutting speed increases. They found that viscoelastic properties affect surface roughness of machined surfaces. In these previous studies, the effects of properties and machining parameters on the machinability of some polymers have been investigated. However, it is very difficult to process all polymer materials under the same conditions due to the wide variety of polymers with distinct mechanical properties. In addition, so far, very few studies have been done for understanding the machinability of polymers, especially PMMA, in micro/nano-scale machining.

Currently, the machining conditions of ultra-precision diamond turning of polymers are often based on the experience in metal cutting[5].

In this study, we attempted to investigate the basic cutting mechanisms of PMMA in ultra-precision diamond turning. The clarification of the fundamental processing characteristics of PMMA is expected to contribute to the realization of high-precision optical polymer lens processing.

2. Experimental setup and conditions

In this study, plane cutting experiments were performed by using ultra-precision lathe Nanoform X (AMETEK Precitech Inc.). A PMMA disk with a diameter of 30 mm and a thickness of 3 mm was used as the workpiece. Cutting conditions are shown in Table 1. Oxygen-free copper (Cu), which has good machinability, was used as a comparison material in feed rate variation experiments. A single-crystal round-nosed diamond tool with a nose radius of 1 mm and a rake angle of 0° was used. After cutting, the machined surface and chips were observed using a scanning electron microscope (SEM), and the surface roughness of the machined surface was measured using a white light interferometer. Figure 1 shows the cutting model of the round-nosed tool. Theoretical surface roughness R_z and undeformed chip thickness $h_{\max}$ of machined surface are affected by nose radius R, feed rate f, and depth of cut d, which can be calculated from equations (1) and (2), respectively. In the experiments, maximum cutting thicknesses were varied at 140, 690, and 1360 nm.

$$R_z = \frac{f^2}{8R} \#(1)$$

$$h_{\max} = R - \sqrt{R^2 + f^2 - 2f\sqrt{2Rd - d^2}} \#(2)$$

The machining atmosphere during cutting was dry with an air jet, and chips were collected without air jet. Although a wet process using cutting oil also exists for the machining atmosphere, the dry process was adopted for PMMA machining because the use of cutting oil reduces the transmittance[6].

3. Results and Discussion

3.1 Effect of feed rate

Table 1 Cutting conditions

Cutting tool	Round-nosed diamond tool
Nose radius R [mm]	1
Rake angle [°]	0
Depth of cut d [μm]	10
Feed rate f [μm/rev]	1, 5, 10
Cutting speed V [m/min]	70, 250
Undeformed chip thickness $h_{\max}$ [nm]	140, 690, 1360
Cutting atmosphere	Dry

Figure 2 shows the relationship between feed rate and surface roughness at cutting speed V =250 m/min measured with a white light interferometer. In oxygen-free copper cutting, surface roughness improved with lowering feed rate according to Equation (1). On the other hand, the surface roughness of PMMA worsened with a lowering feed rate. And the reason for this peculiar trend in PMMA can be explained by the schematic diagram of the cutting process for a small feed rate (f =1 μm/rev) shown in Fig. 3. Equation (2) shows that when the feed rate is small, $h_{\max}$ also decreases. In this case, the cutting area becomes smaller, and therefore the amount of energy consumed during cutting becomes smaller. The specific energy α is defined by Equation (3).

$$\boldsymbol{\alpha} = \frac{\boldsymbol{E}}{\boldsymbol{V'}} \#(\mathbf{3})$$

where E is the energy consumed during cutting and V' is the volume of material cut away during cutting.

As the cut thickness decreases, both energy E and volume V' decrease. However, because of size effects, the relationship between α and V' is inversely proportional, and the specific energy is expected to increase as the cutting volume decreases. The phenomenon that specific cutting resistance increases with decreasing cutting thickness at micro/nano scale undeformed chip thickness was also reported from other researchers[7,8,9]. In addition, specific cutting resistance can be considered as the cutting energy per unit cutting volume. Since cutting volume also decreases as undeformed chip thickness decreases, the relationship between specific energy α and volume V' shows the same tendency as the relationship between specific cutting resistance and undeformed chip thickness. Then, specific energy is considered to increase as the feed rate lowers. Since energy is converted to cutting heat during cutting, when specific energy

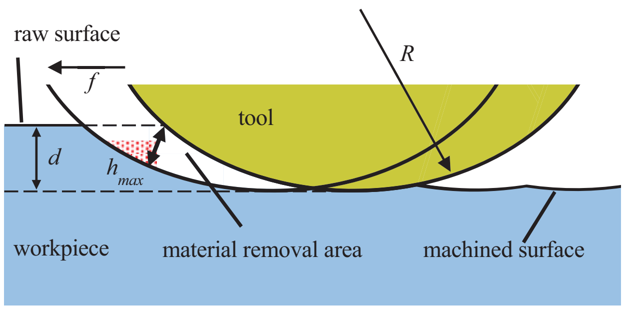


Fig. 1 Cutting model of a round-nosed tool

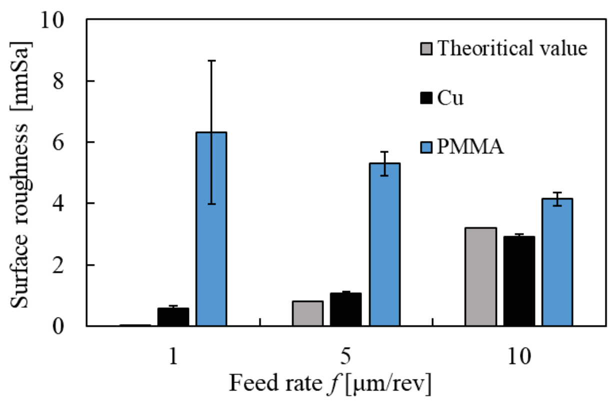


Fig. 2 Relationship between cutting speed and surface roughness

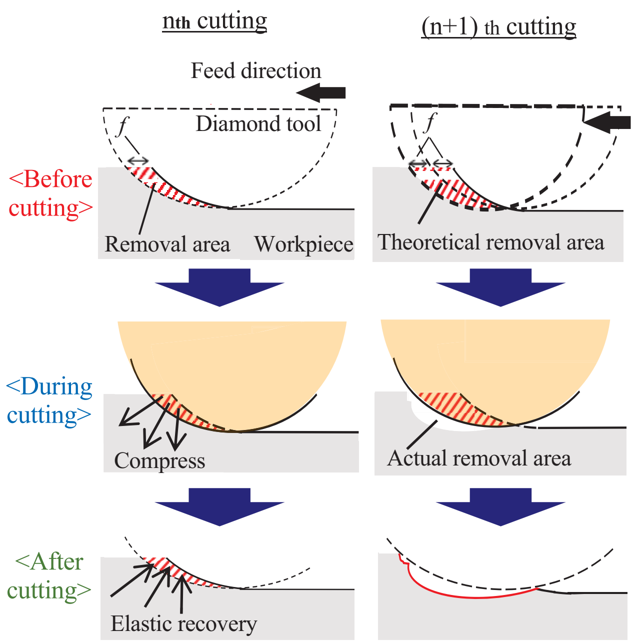
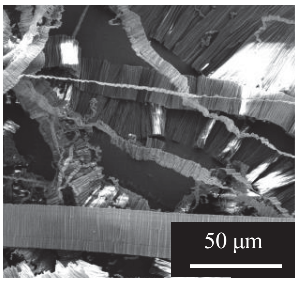
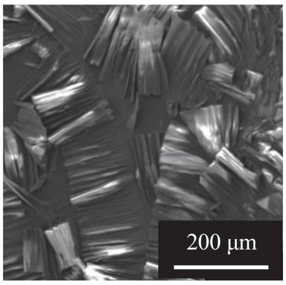


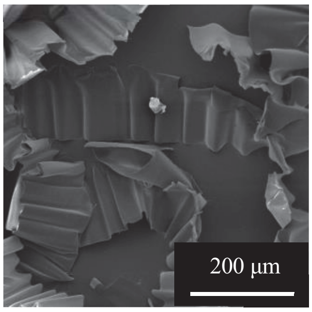
Fig. 3 Cutting models for condition f = 1 μm/rev



(a) f = 1 μm/rev



(b) f = 5 μm/rev



(c) f = 10 μm/rev

Fig. 4 Cutting chip morphology at different feed rates

increases, cutting heat increases, raising the temperature of the material. It has been reported that PMMA is a thermoplastic polymer with a glass transition temperature of 105°C, which softens as the temperature rises and the temperature has a significant effect on the mechanical strength of materials[10,11]. Therefore, it is considered that as the feed rate lowers, the material temperature rises and softens due to the size effect. As shown in Fig. 3, when small feed rate (f = 1 μm/rev), cutting is not stable due to material softening and edge rounding, and the material is partially compressed into the inner part, and elastic recovery occurs after the cutting. Thus, cutting was not stable: in the previous cutting path, the part of the material deformed and recovered, causing no material removal. In the current cutting path, the part that was not removed in the previous cut was removed in current cut together, leading to two times cutting area. As a result, surface defects are generated, and the surface quality of the machined

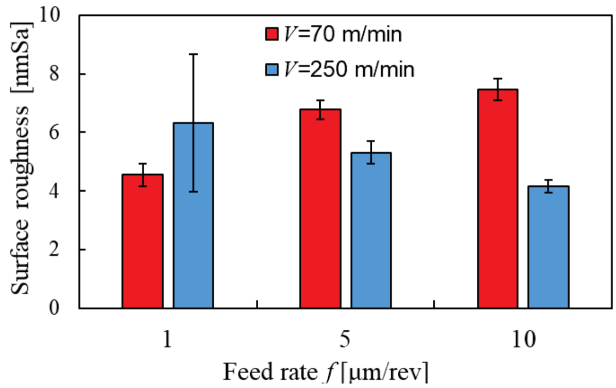


Fig. 5 Relationship between feed rate and surface roughness at different cutting speeds

surface deteriorated. Figure 4 shows SEM images of chips at different feed rates when V = 250 m/min. The flow-type chips, which indicate ductile mode cutting, were observed at all feed rates. However, chips with uneven widths were observed in Fig. 4(a). This comfirms that machining is not stable at a small feed rate (f=1 μm/rev). And also, this is thought to be due to the occurrence of the non-cutting area as described in Fig. 3.

3.2 Effect of cutting speed

The relationship between surface roughness of the machined surface and feed rate at different cutting speeds is shown in Fig. 5. At a lower feed rate (f = 1 μm/rev), the surface finish was improved to less than 5 nm Sa when decreasing the cutting speed. Because polymer materials have viscoelasticity, the strain rate and cutting heat tend to increase as the cutting speed increases[3)], and the cutting heat generated in cutting softens the surface of the material. Therefore, it is assumed that surface roughness can be improved by decreasing the cutting speed and suppressing the generation of cutting heat. In contrast, when the feed rate was relatively large (f = 10 μm/rev), surface quality became worse as the cutting speed decreased. This was the opposite trend for f = 1 μm/rev. The reason for this different trend is thought to be related to the effects of material softening due to both size effects and cutting heat. At f = 1 μm/rev, the material is easily softened by the size effect. Therefore, at V = 250 m/min, the surface quality deteriorated due to softening and elastic recovery caused by the size effect and cutting heat. However, when f = 10 μm/rev, the softening of the workpiece material due to size effects is not significant. Thus, compared to V = 250 m/min case, the surface roughness increased at V = 70 m/min due to partially brittle mode cutting because the mean cutting heat was relatively reduced, and the material was not sufficiently softened and was remained hard. So, it is considered that the opposite trend was observed with f = 1 μm/rev. Figure 6 shows SEM images of the machined surface at f = 1, 5 and

10 μm/rev. At f = 10 μm/rev, surface defects were observed on the machined surface. This indicates that brittle mode cutting was partially performed due to the decrease in cutting speed at f = 10 μm/rev. By contrast, when f = 1 μm/rev, the machined surface became smooth. This is because the decrease in cutting speed at f = 1 μm/rev suppressed elastic recovery and made the cutting became more stable. Also, at f = 5 μm/rev, the effect of cutting speed on surface roughness is small, suggesting an intermediate state between f = 1 and f = 10 μm/rev. It can be inferred that using this feed rate as a boundary, surface roughness can be improved by increasing the cutting speed for larger feed rates (f =10 μm/rev), and by decreasing the cutting speed at lower feed rates (f =1 μm/rev).

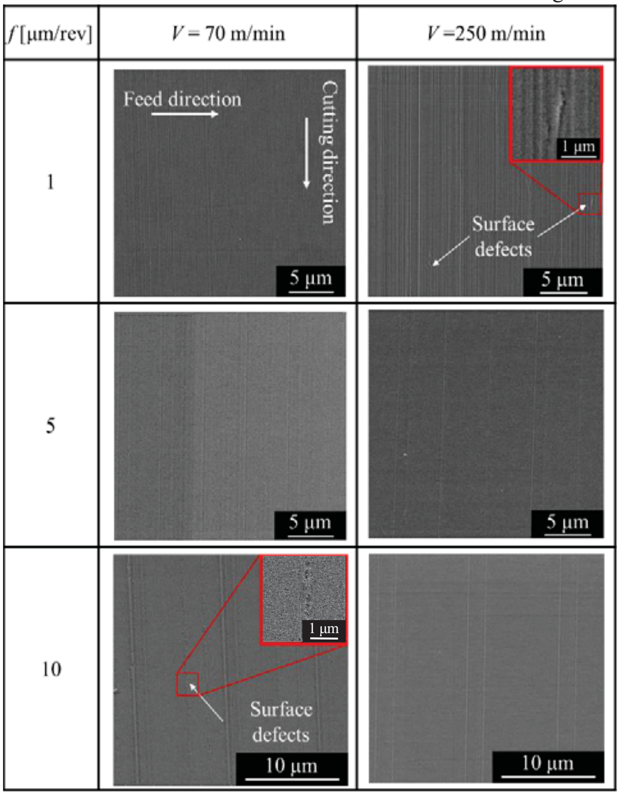


Fig. 6 SEM images of machined surface at f = 1, 5, 10 μm/rev

4. Conclusions

This study investigated the effects of feed rate and cutting speed on fabrication of optical surfaces on PMMA by ultra-precision cutting. As a result, the following conclusions were obtained.

(1) At a cutting speed V = 250 m/min, the surface roughness improved as the feed rate increased, showing the opposite trend to the theoretical value.

(2) At a feed rate f = 1 μm/rev, the surface roughness of the machined surface decreased as cutting speed decreased. A surface roughness of lower than 5 nm Sa was achieved, which meets the requirement of optical lenses. On the other hand, at feed rate f = 10 μm/rev, the surface roughness of the machined surface increased as the cutting speed decreased.

(3) Although flow-type chips were obtained at all feed rates, chips with uneven widths were observed at a feed rate of f = 1 μm/rev, indicating that the cutting process was unstable when the feed rate is too small.

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