Ductile-Regime Turning of Brittle Materials by Single Point Diamond

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1. Introduction

To realize new types of optical devices having minute patterns above aspheric profiles, a new precision cutting technique for optical glass is required. It is well known that brittle materials, such as glass or silicon, can be machined crack free when the depth of cut is fixed at less than a certain critical amount1). This is called ductile mode cutting. There have been many studies on the brittle-ductile transition process to clarify the mechanism of brittle material machining or develop manufacturing techniques for ductile mode cutting. Blake and Scattergood investigated the critical depth of cut for single crystals of germanium and silicon using a diamond-turning lathe2). Brinksmeier et al. experimentally tested a plunge-cut technique for silicon and germanium3). Schinker cut several types of glasses using high-speed radial cutting with single diamond tools4).

This report presents our experimental results on the machining of brittle materials using a practical ultra-precision lathe. Four machining types comprising subdivisions of ductile and brittle modes were defined to provide detailed descriptions of the experimental results. Machining experiments on BK7 and SiC were conducted in several different atmospheres. The maximum depth of groove in the ductile mode and the critical depth of tool indentation calculated from previous theoretical analysis were compared.

2. Outline of Experiment

2.1 Experimental procedure

Fig. 1 shows the experimental setup in this study. This system is an ultra-precision lathe with a fast tool servo (FTS) for single point diamond turning. Using a piezoelectric actuator, the FTS can control depth of cut at a 2 nm resolution, and its frequency response is 2 kHz. A diamond cutting tool is set on the FTS. The radius of the cutting tool is 0.2 mm, and the rake angle is 0 degree. The rotation speed of the spindle axis is 90 rpm.

The work is attached to the spindle axis by a vacuum chuck. In this study, BK7, SiC, and vitreous silica were used for cutting work. The diameter of these works was 30 mm, and the hickness was 5 mm.

The computer input a command signal with a profile like the teeth of a saw, as shown in Fig. 1, to the servo system, and an inclined plunge cut was applied to the work material three times per rotation. The cutting depth was 4 microns.

Before cutting, several types of reagents were applied to the surface of the work, and the machining atmosphere was changed. In this stury, eight machining atmospheres were selected: dry, water, heptane, octane, methanol, ethanol, and propanol for the BK-7 and SiC cutting experiments, and triethylamine for BK-7 only. Changing the cutting radius, we conducted three cutting experiments with each atmosphere. In this manner we obtained nine grooves of inclined plunge cut for each atmosphere.

After the cutting experiments, the surfaces of the works were observed by Nomarski differential interference microscope, and the machining types, as described in the next section, were distinguished. The amount of tool infeed was calculated from the starting point of the cutting mark, and depth of groove

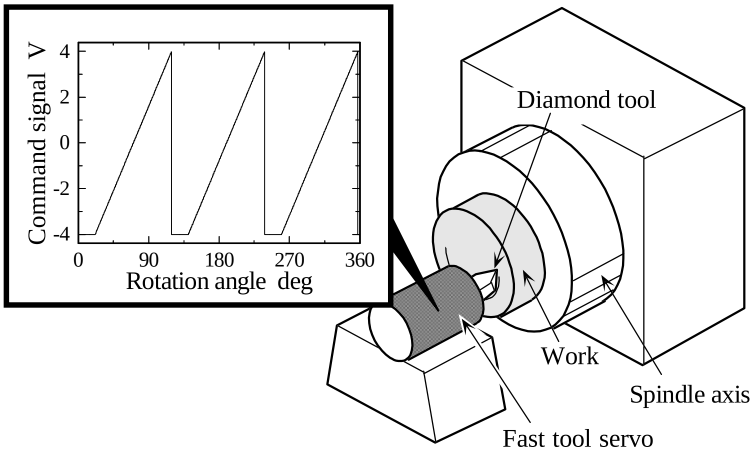


Fig. 1 Ultra-precision lathe with fast tool servo

was measured by a surface topographic measurement apparatus (Talyscan, Rank Taylor Hobson). The resolution of this apparatus is 3 nm. Finally, we obtained the relationships under several types of atmospheres between tool infeed, depth of groove, and groove state.

2.2 Definition of machining types

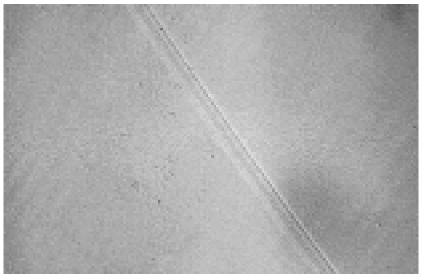
The brittle mode or ductile mode is confirmed when a brittle material is machined. These two modes are distinguished according to whether cracks or damage occur in the machined surface. In this study, four machining types comprising subdivisions of ductile and brittle modes were defined to provide detailed descriptions of the experimental results.

Figs. 2(a) to (d) show typical machining types. These results were obtained by Nomarski microscope observation. Type 1 has narrow grooves with no cracks. This type occurs by plastic deformation of the surface material. Almost all cases of this type have a depth of less than 100 nm. Type 2 has wider and deeper grooves than type 1, but also it has no damage. This type is realized in ductile mode, and is the most suitable machining type for damage-free machining of brittle materials. Type 3 has damaged grooves with lateral cracks. There are some cracks around the grooves, but no major destruction in the grooves. Type 4 is overall brittle mode machining. Many cracks and factures are confirmed around the grooves.

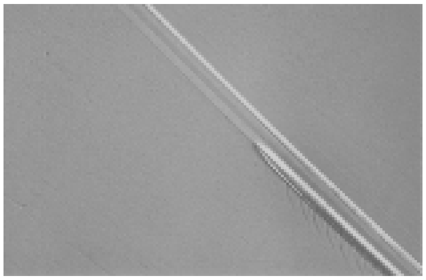
3. Results

3.1 BK7 cutting experiments

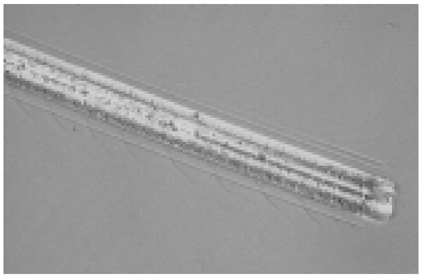
Fig. 3 shows the results of the BK7 cutting experiments in a water atmosphere. The tool infeed is plotted on the x axis, and the depth of the cut measured by Talyscan on the y axis. Both of the axes are denoted in logarithmic values. The line in this graph is y = x, indicating the same value for depth of groove and tool infeed.



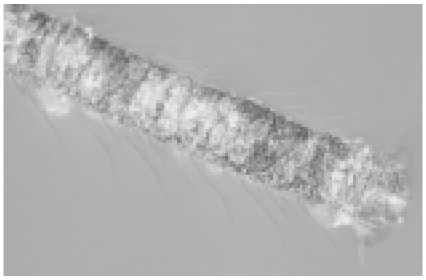
(a) Type 1



(b) Type 2



(c) Type 3



(d) Type 4

Fig. 2 Machining types in brittle material cutting

From this figure, it is clear that except for type 4, the depth of groove is less than the tool infeed, because of the compliance of the lathe. In the case of type 4, there is a large fracture in the groove, so the depth of groove is larger than the tool infeed. The depths of grooves for type 1 and type 2 differ by about 0.5 to 0.7 micron at the same tool infeed. This results from the spring back of the material in type 1, and the fact that the tip of the cut material in type 2 flows on the rake plane of the cutting tool. In the case of type 2, although a part of this area overlaps with type 3, an almost linear relationship is obtained between the tool infeed and depth of groove. If individual type 2 can be obtained, ductile mode cutting will be realized.

Fig. 4 shows the results under several types of atmospheres. This figure shows how the four machining types are obtained in each atmosphere. Under dry condition, no individual machining type is obtained at 0.2 micron. Stable cutting therefore cannot be expected in this atmosphere. In the heptane, octane, methanol, and ethanol atmospheres, however, there are areas in which individual type 2 can be obtained. Especially in the methanol and ethanol atmospheres, such areas exist from 0.2 to 1.2 microns, indicating good atmospheres for practical machining. Using propanol, however, type 2 is covered by type 3 from 0.25 micron, so that it is not suitable for stable machining. Under a triethylamine atmosphere, type 3 exists from 0.2 micron cutting. It therefore appears that this condition is not good for ductile machining. In microscopic observations, no cracks were found around the groove although many cracks could be observed inside the groove. Hence, it is considered that crack propagation is the main machining mechanism of this atmosphere.

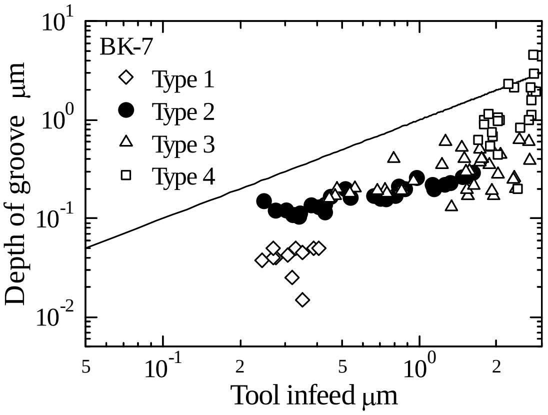


Fig. 3 Results of cutting experiments (BK7)

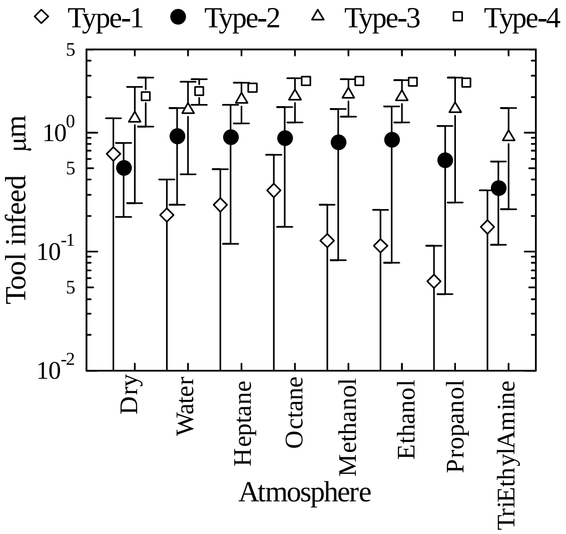
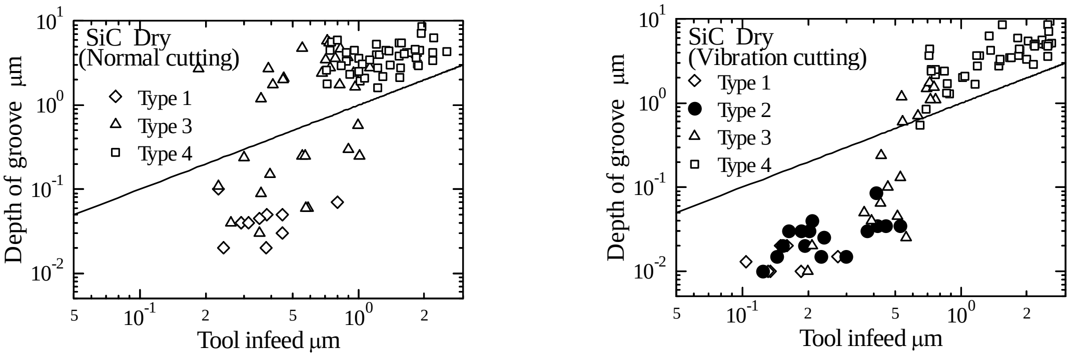


Fig. 4 Machining types under various atmospheres

3.2 SiC cutting experiments

We conducted the same experiments on SiC as for BK7. No significant difference was observed except under dry condition, indicating that SiC is a material that is less affected by the atmosphere compared with BK7.

Figs. 5(a) and (b) show two sets of machining results under a dry atmosphere. Fig. 5(a) shows normal cutting, and Fig. 5(b) shows vibration cutting, which was realized by the addition of FTS minute vibrations to the plunge cut. The amplitude of vibration was 0.1 micron in the cutting direction. From (b), it can be seen that the type 2 cutting groove can be obtained at 0.1 to 0.5 micron tool infeed. The reason for this result is that minute cutting reduces the friction between the cutting tool and the material.



(a) Normal cutting (b) Vibration cutting

Fig. 5 Results of cutting experiments (SiC)

3.3 Relationship between experimental results and theoretical values

Under a water atmosphere, BK7, SiC, and vitreous silica were cut and each maximum depth of groove in type 2 was observed. Table 1 shows the results.

This table also shows the critical depth of indentation calculated from Griffith's theory. This value is calculated as follows.

$$d_c \approx \frac{E}{H_V}\left(\frac{K_{IC}}{H_V}\right)^2$$

Table 1 Calculated d_c and observed results

Materials			BK7	SiC	Vitreous silica
Fracture toughness	K_{IC}	MPa m$^{1/2}$	0.2	4	0.75
Young's modulus	E	GPa	81.5	420	70
Hardness	H_V	GPa	5.1	24	6
Critical depth of indentation	d_c	µ m	0.025	0.49	0.18
Observed maximum depth of groove in type 2		µ m	0.2	0.5	0.1

From this table, it is seen that nearly the same values of depth are confirmed for SiC and vitreous silica. On the other hand, the observed value for BK7 significantly differs from the theoretical value. However, there is a report that the maximum depth of cut in BK7 ductile mode was 0.25 micron at a rake angle of 45 degrees and a cutting speed of 20 m/s[3]. The result of our experiment is close to this result. It is therefore considered that the critical depth of cut in BK7 becomes much larger than the indentation.

4. Summary

This study report describes our experimental results on the machining of optical glasses and brittle materials for the realization of brittle material machining. BK7 and SiC were cut in several different atmospheres by an ultra-precision lathe. For BK7, methanol and ethanol provided the best conditions for ductile cutting. Vibration cutting was effective for SiC dry cutting. The relationship between the observed maximum depth of groove in type 2 and the calculated critical depth of indentation was investigated. In the case of SiC and vitreous silica, nearly the same values for depth were confirmed, whereas the values for BK7 were significantly different.

References

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