

PROFILE GENERATION FOR BRITTLE MATERIALS BY USING ULTRA-PRECISION LATHE WITH ON-MACHINE MEASUREMENT SYSTEM

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1. Introduction

Ductile mode machining¹⁾ of brittle materials, such as optical glasses, enables high-precision optical devices to be produced without the use of a mold. Compared to grinding, single point diamond (SPD) turning is more suitable for high-spatial-frequency profile generation. Therefore, if a ductile mode machining technique employing SPD is established, it will become possible to fabricate new types of optical devices having minute patterns on aspheric profiles.

We have previously presented our experimental results on the machining of brittle materials using a practical SPD ultra-precision lathe with a fast tool servo (FTS)²⁾. In that study, the plunge-cut experiment³⁾ was performed on brittle materials in several different atmospheres, and it appeared that an ethanol atmosphere was best for BK7 cutting. However, the depth of cut in the experiment was denoted only by the tool infeed, so the effect of the surface profile or skew angle when the work was attached to the chuck was not taken into account. For exact control of the depth of cut, information on the surface profile is important.

In the present study, we constructed an on-machine measurement system to measure the surface profile before cutting. This system can create the cutting data from the measurement results. By applying profile measurement results to plunge-cut experiments on brittle materials, it was confirmed that our system enables works to be cut without being affected by the surface profile.

A profile generation experiment on brittle materials was performed taking the profile surface into consideration. This was a preparatory experiment for generating minute patterns on an aspheric profile. A concave micro lens array was cut on the surface profiles. After machining, generation of the lens array was confirmed by interferometric observation.

2. Ultra-precision lathe with on-machine measurement system

Fig. 1 shows a schematic diagram of the ultra-precision lathe with the on-machine measurement system. Using a piezoelectric actuator, the FTS can control depth of cut at a 2 nm resolution, with a frequency response of 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. Contact between the FTS diamond bite and work surface is detected from changes in the servo signal.

A capacitance type sensor is set by the side of the FTS and scans the surface of the work by main axis rotation and x-axis slide feeding. By using a double-buffered DAQ (data acquisition) board synchronizing main axis encoder pulse, this system can measure 2048 points per 1 rotation. The rotation speed of the spindle axis is 90 rpm. The feeding speed of the x-axis slide in measurement was set at 1.0 mm/min in all of the experiments.

The data sampling sequence of the double buffer is as follows: The first buffer in the double buffer acquires data until the buffer is filled up. When the first buffer is filled, the second buffer starts to acquire data. The computer saves the data of the first buffer to a file while the second buffer is acquiring data. When the second buffer is filled, the same procedure is performed. The double buffer repeats these operations and records data.

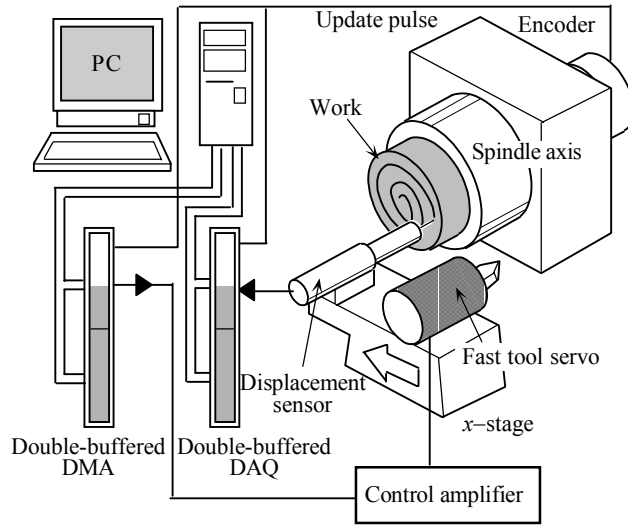


Fig. 1 Ultra-precision lathe with on-machine measurement system

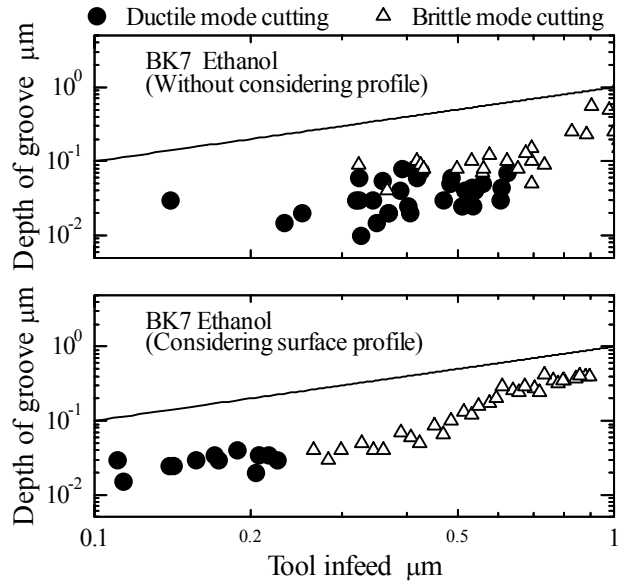


Fig. 2 Results of plunge-cut experiments

The amount of tool feeding is determined with reference to the profile data of each point. Therefore, the FTS can ensure the exact depth of cut for the work without being affected by the surface profile or setting errors.

The cutting data are sent to the double-buffered DMA (direct memory access) board. The DMA operates similarly to the DAQ board. It outputs a data stream to the control amplifier using two buffers.

3. Results of plunge-cut experiments

Plunge-cut experiments were performed to demonstrate the validity of our system. In these experiments the FTS applied the plunge-cut to the work increasing the depth of cut with the main axis rotation. BK7 was selected as the work for cutting. Before cutting, the test work was measured by the on-machine measurement system. The tool infeed data were generated so as to make the amount of infeed for the test work linearly increase with the main axis rotation. Cutting was performed three times at different radii.

After the cutting experiments, the surfaces of the test works were observed by Nomarski differential interference microscope, and the transition from ductile mode cutting to brittle mode cutting was identified. The amount of tool infeed was calculated from the starting point of the cutting mark, and a surface topographic measurement apparatus was used to measure the depth of groove. In this way, the relationships between tool infeed, depth of groove, and groove state under several atmospheres were finally obtained.

Fig. 2 shows the results of the plunge-cut experiments. In this figure, two results — without considering the surface profile, as in the past method, and considering the surface profile— are shown. Comparing these results, it is clearly seen that the ductile mode widely overlaps the brittle mode when the surface profile is not considered.

Of course, some area of overlap between the ductile and brittle modes is to be expected, because these results were obtained from three cutting marks, and the respective ductile-brittle transitions affected by the crack distribution are not perfectly identical. However, the results show overlaps occurring at a depth of cut of 300 nm or more. The reason is, as shown in Fig. 3, that plunge-cut tool infeeding was affected by the profile of the work surface, and the real depth of cut was different from the expected value.

On the other hand, when the profile of the work surface is taken into consideration, there is no overlapping between the ductile and brittle modes. This shows that the effect of the surface profile was

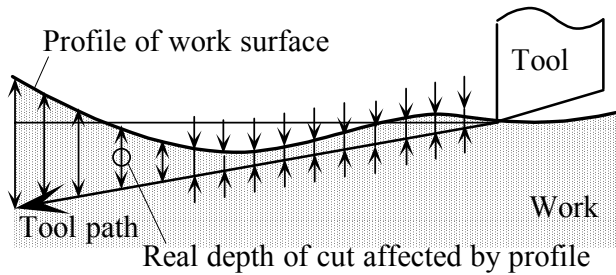


Fig. 3 Schematic diagram of plunge cut

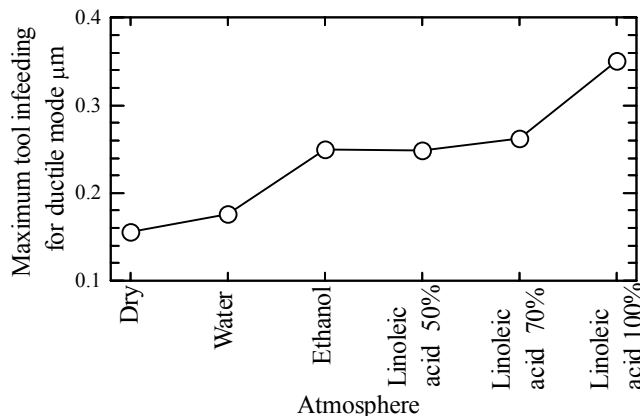


Fig. 4 Plunge-cut experiment under several atmospheres

Linoleic acid is a much better atmosphere, however, with concentrations 50% and 70% providing similar or slightly better results than ethanol.

We believe that these results are mainly attributable to a reduction of friction between the material surface and the cutting bite. Reduced friction causes less crack propagation and increases the maximum depth of cut in ductile mode. In addition, a chemical effect on the glass surface can be expected.

5. Profile generation experiment

Using an ultra-precision lathe, a basic profile generation experiment was performed on brittle material. In this study, a concave micro lens array was selected for profile generation. The material used was soda lime. The diameter of the material was 30 mm, and that of the machined area was 23 mm. The feeding speed of the x-axis in the ultra-precision lathe was set at 0.4 mm/min. The cutting atmosphere was linoleic acid diluted to 50% by ethanol.

Fig. 5 shows the cutting data chart for the FTS. This chart includes the profile surface to maintain ductile mode cutting. The maximum depth of cut was 250 nm. The diameter of each lens was 300 micron, and the interval of each lens was 200 microns.

The result of the profile generation experiment is shown in Fig. 6. This figure shows the measurement result obtained by WYKO interferometer (NT-2000). Throughout the cutting area there is almost no brittle cutting zone, but ductile mode cutting marks.

Fig. 7 shows section profiles of the micro lens. These profiles should correspond because the cutting data for the micro lens was symmetric with the center axis of each lens. But Fig. 7 does not show good correspondence.

The reason is that the tip of the cutting bite changes due to wear, so that the motion copying of the cutting bite was not performed perfectly. Indeed, observation under a microscope after cutting showed

cancelled by the generation of cutting data from the on-machine measurement results. These results demonstrate the validity of the on-machine measurement system and assure the reliability of the experimental results.

4. Effect of cutting atmosphere

In our previous study, we obtained the result that ethanol provided the best condition for ductile cutting of BK7, even if these results were affected by the profile of the work surface.

This time, we performed plunge-cut experiments under several atmospheres, taking the surface profile of the work into consideration. The test work was soda lime, and the atmospheres selected were dry, water, ethanol, and linoleic acid. The linoleic acid was diluted by ethanol, to give concentrations of 50%, 70%, and 100%.

Fig. 4 shows the results of the experiments. This figure shows the maximum tool infeed for ductile mode under several atmospheres. The dry and water atmospheres are not suitable for ductile cutting mode, whereas ethanol is a good atmosphere in these experiments also.

Output filename : [AUG7CUT.CDT]
 Title : [SLAug7 cutting data]
 Workpiece diameter : 23.0 (mm)
 Number of tracks : 2587
 Angular segmentation : 4096
 Feed rate : 0.40
 Pulse rate : 6300

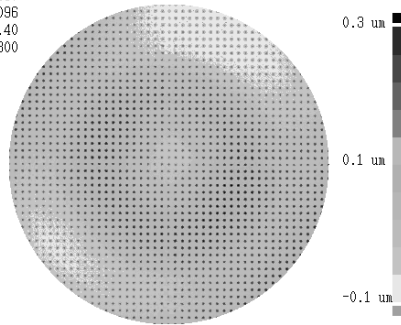


Fig. 5 Cutting data chart for the profile generation

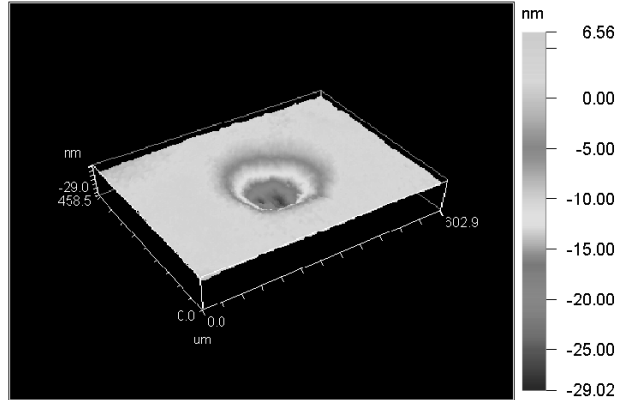


Fig. 6 Results of profile generation experiment

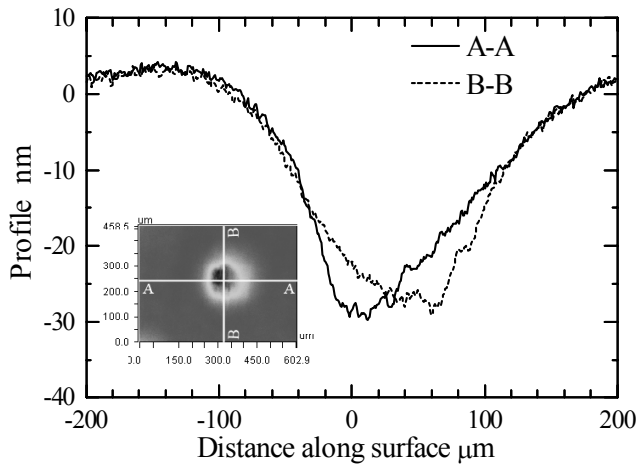


Fig. 7 Section profiles of micro lens

wear of the cutting bite.

The maximum depth of the lens is almost 30 nm. This result has validity because, as seen in the relationship between tool infeed and depth of groove in Fig. 2, the depth of groove will be 30 nm when the tool infeed is 250 nm, allowing maximum tool infeed in ductile mode. Of course, Fig. 2 shows the results for BK7 under an ethanol atmosphere, not soda lime under linoleic acid and ethanol. But almost the same relationship was obtained for this material and atmosphere.

In this experiment, only nanometer-order depth of profile was obtained. To fabricate a practical optical device, at least micrometer-order profiles are required. A deeper form without brittle cracks will be obtained by carrying out repetitive cutting.

6. Summary

This study can be summarized as follows.

- (1) We have constructed an on-machine measurement system for an ultra-precision lath. Plunge-cut experiments showed that our system is able to cut works without being affected by the surface profile.
- (2) The effect of the cutting atmosphere was investigated. For dry, water, and ethanol atmospheres, the same tendencies were obtained as in our previous study. Linoleic acid provides the best atmosphere for soda lime.
- (3) A profile generation experiment was performed. In this study, a micro lens array on the profile surface was tested. For almost all cut surfaces, a ductile mode lens array was obtained. The profile of the lens was not symmetrical with the center axis of each lens. The main reason for this is wear of the cutting bite.

References

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