Development of a Micro Cutting and Deforming System for Glass Materials
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1. Introduction
Many papers have been reported concerning the ductile mode cutting. Yoshino et al. have reported that the critical depth of cut became larger in case of cutting a single crystal silicon under the high hydrostatic pressure condition [1]. The atmosphere dependency of the cutting mode for an optical glass has been investigated [2]. By the way, it has been reported that brittle materials, especially a glass material, present a plastic deformation manner at the nano to micro scale as well as a ductile cutting mode [3,4]. The characteristic feature has been verified mainly by the Vickers indentation or scratching test. A development of a system that can realize ductile mode cutting and deformation at the nano to micro scale will contribute very much to produce nano/micro optical devices or modify a part of geometry of optical parts. The paper deals with the micro cutting and deforming system for brittle materials.

First, the paper explains the configuration of the developed system to be a shaper which can realize a nano-meter order depth of cut. Especially, the mechanism and method to determine the depth of cut in nano-meter order is explained. Using the system, some cutting experiments conducted are presented. Experiments with the small inclination of the workpiece to give a gradual increase of the depth of cut show that there are three characteristic phases during the cutting. These are characterized as follows: (i) only the thrust component of cutting force is measured, (ii) the principal and thrust components of cutting force are measured and (iii) the variance of cutting force becomes larger. Machined surface conditions observed by a laser micro scope and a surface profiler corresponding to the three phases are examined. Especially, the phase (i) seems to be deformation by densification of a glass. In the last of the paper, an application cutting using the phase (i) to make a groove is presented.

2. Experimental setup
Figure 1 shows the experimental setup. The developed system consists of a linear motor driven tool feed system, a hybrid-type tool positioning unit, a workpiece alignment unit, a piezolectric type three-axis force sensor (model type 9256A1, Kistler Ltd.).

The hybrid-type tool positioning unit consists of coarse and fine positioning units, a capacitance type displacement sensor (model type 5401, Japan ADE Ltd.) and a laser displacement sensor (model type LC2430, Keyence Ltd.) shown in Fig.1(b). The coarse
positioning unit using a ball screw with 1mm lead is installed for tool setup and rough approaching.

The fine positioning unit with a piezo-electric actuator and a capacitance type displacement sensor determines the depth of cut. The displacement sensor is installed to detect the displacement of the cutting tool. In order to determine the depth of cut, the position of the workpiece surface should be measured. To this end, the coarse and fine positioning units and the force sensor are used. Simply speaking, (i) approaching the cutting tool to the workpiece using the coarse positioning unit, (ii) when the force reaction is measured, retracting the cutting tool once using the fine positioning unit in finer step, (iii) approaching the cutting tool to the workpiece again using the fine positioning unit, (iv) when the force reaction is measured, the position can be estimated as the position of the workpiece surface.

The laser displacement sensor is used to check the inclination of the workpiece, scanning the workpiece by the laser displacement sensor. The stage can control the orientation of a workpiece by adjusting four screws installed at each corner of the table.

Rigidity of the workpiece alignment unit and tool positioning unit in cutting depth direction are 10.03N/μm and 2.20N/μm respectively.

3. Experimental results

Cutting experiments using the developed system have been conducted. The workpiece material is soda-lime glass. Specification of the cutting tool used in the experiments is shown in Table 1. Various feed speeds are examined from 1mm/s to 500mm/s.

![Experimental setup](image)

(a) Overview of the system  (b) Macrograph around the cutting tool

Fig.1 Experimental setup
Table 1 Specifications of the cutting tool

<table>
<thead>
<tr>
<th>Tool angle</th>
<th>118 deg.</th>
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</thead>
<tbody>
<tr>
<td>Rake angle</td>
<td>-30 deg.</td>
</tr>
<tr>
<td>Nose radius</td>
<td>1.5mm</td>
</tr>
<tr>
<td>Edge radius</td>
<td>less than 80nm</td>
</tr>
<tr>
<td>Material</td>
<td>Single crystal diamond</td>
</tr>
</tbody>
</table>

3.1 Deformation and ductile to brittle transition in various feed speeds

A workpiece is set with the inclination as 1um per 20mm in feed direction on the alignment unit in order to realize a gradual increase of the depth of cut. Figure 2 shows a principal (Fx) and thrust (Fz) components of the cutting force measured by the force sensor and their variance. It is observed in Figure 2 that there are three characteristic phases during the increase of the depth of cut. These are characterized as follows: (i) only the thrust component of cutting force is measured, (ii) the principal and thrust components of cutting force are measured and (iii) the variance of cutting force becomes larger. The characteristics seem to be common even if the feed speeds are different. After the thrust component becomes larger than 500mN, the principal component can be measured in any cases. The increase ratio of the thrust component in the phase (i) is smaller than that in the phase (ii).

![Graphs showing cutting force at different feed speeds](image-url)
Figure 3 shows the machined surface profiles in case of the feed speed 1mm/s as a representative case. The machined surface profiles are observed by a laser microscope (model type VK-8550, Keyence Corp.) and a surface profiler (model type SURFCOM 570A, Tokyo Seimitsu Ltd.) corresponding to the three phases. From the figure, the phase (iii) represents brittle mode cutting clearly. The phase (i) seems not to have any crack observed on the machined surface although it should be examined by means of etching tests. The machined surface in the phase (ii) has some bosses on it which are observed by the laser microscope.

3.2 Deformation and ductile to brittle transition in various rake angles

The influence of rake angles of the cutting tool on the phases observed in 3.1 has been also examined. Figure 4 shows the cutting forces acquired in the experiments in which various rake angles of the cutting tool are taken as -15, 0, 5 deg. In case of -15 deg., it can be observed that there is a small region corresponding to the phase (i). However, in case of other rake angles, the phase (i) cannot be observed. From the results, it can be said that the emergence of the phase (i) would be strongly influence by the rake angle of the cutting tool not by the feed speed.
3.3 Application by means of the first phase

We tried to make deeper groove applying the first phase repeatedly. Specifically, the feed speed was 1mm/s and the cutting tool with the rake angle -30 deg. in 3.1 was used. The grooving was repeated five times. Figure 5 shows the cutting results. It can be observed that the realized depth of cut is 200nm and the cross section of the groove is very smooth.

3.4 Discussions

It is very interesting that there are three phases during the increase of the depth of cut characterized by the cutting force and surface profile. Among the three phases, the first phase in which only the thrust force can be measured should be very important for nano-micro machining for glass materials. Whether the first phase is categorized into deformation or ductile mode cutting should be discussed carefully by taking material analyses. However, it can be suggested that the first phase may be deformation, because the emergence of the phase depends on the rake angle and the principal component cannot be measured. If the cutting chip is generated, both components of cutting force should be measured. Another measure to make it sure is to use video camera observing the cutting chip generation in real time. It will be a future topic. To discuss whether plastic flow or densification produces the deformation [3] is also interesting to understand the phase in deep.
4. Conclusions

A micro cutting and deforming system has been developed. Through some cutting experiments and observation of cutting force and machined surface profile, it was found that there are three phases during the increase of depth of cut in nano-meter order. Especially, the first phase was very interesting because only the thrust component could be measured and the machined surface was very smooth. Although further analyses should be conducted, the phase would be important to make nano-micro structure of glass materials.

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References