Development of Micro Ultrasonic Abrasive Machining System*
(1st Report, Studies in Micro Ultrasonic Abrasive Machining)

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This paper deals with the development of a micro ultrasonic abrasive machining system. The size of every component for opto-electrical devices or micro electro-mechanical systems (MEMS) has been reduced in recent years due to progress in opto-digital communications technology. The demands for micro-sized holes, slits and 3D structures of hard brittle materials such as ceramics and glass are considerable. In this study, a micro ultrasonic abrasive machining system was developed, which has an aerostatic ultrasonic vibration spindle, 3-axis NC sliding tables, dynamometer for machining pressure control and on-machine shaping system for small-diameter tools. The tools (0.03-1.0 mm in diameter) and ultra-fine SiC slurry are used in the micro ultrasonic machining, and basic characteristics in micro-hole machining of glass are investigated. As the tool diameter becomes smaller, the machining speed and tool wear become the worse. However, rotating the tool doubled the machining speed, and decreased a protrusion left in the center of the machined hole due to cavitation.

Key Words: Non-Traditional Machining, Abrasive Grain, Machinability, Ultrasonic Machining, Micro Mechanical Fabrication, Sub-Milli-Structure, Micro Tool, Slurry, Cavitation

1. Introduction

At present, practical functional silicon structures are fabricated by photoetching. Recently however, there has been an increase in the demand for more complex shapes and materials other than silicon. The size of the machined structures is often less than several millimeters, and the desired materials are often difficult to machine. As the machining of smaller objects requires smaller tools, new problems have emerged such as the manufacture of such tools, and tool wear and breakage. This has stimulated research into new machining processes and the fabrication of micro tools (small-diameter tools). For example, Takeuchi et al.(1) successfully manufactured a diamond ball endmill of 0.1 mm in radius to machine a three-dimensional micro-shape. Onikura et al.(2) used a 20 μm-diameter drill to drill a hole in aluminum alloy by ultrasonic cutting. Masaki et al.(3) developed an ultra-fine electric discharge machine, successfully machining a 5 μm-diameter hole and a 35 μm-wide groove in stainless steel. However, these methods are basically intended to be applied to the machining of metallic materials, and are not suitable for machining brittle materials such as ceramics and glass.

The fabrication of micro-shapes by micro ultrasonic abrasive machining has been examined by a number of researchers as a method applicable to the machining of brittle materials. For example, Etoh et al.(4),(5) successfully manufactured a cemented carbide tool of extremely small diameter by wire electric discharge machining and used the tool to drill a hole of 5 μm in diameter in silica glass and silicon. This was achieved by contacting the tool with the vibrated

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workpiece under a supply of loose abrasives. In this study, we developed an ultrasonic vibration spindle capable of supporting an ultrasonic vibrator unit with an aerostatic bearing and rotating a small-diameter tool with high precision while providing axial ultrasonic vibration. A prototypal machining system was then manufactured that allows the small-diameter tool to be moved in three dimensions under numerical control for the ultrasonic abrasive machining of three-dimensional micro-shapes. In this paper, we machined a micro-hole in glass, and basic machining characteristics including the influence of tool diameter and tool rotation were examined.

2. Problems with Micro Ultrasonic Abrasive Machining and Solutions

Micro ultrasonic abrasive machining is characterized by the use of smaller tools than those used in conventional ultrasonic abrasive machining. This results in a series of new problems and issues such as the manufacture of smaller tools, tool breakage, the mechanism of applying machining pressure, and maintaining adequate supply of abrasive particles between the tool and the workpiece.

2.1 Tool breakage

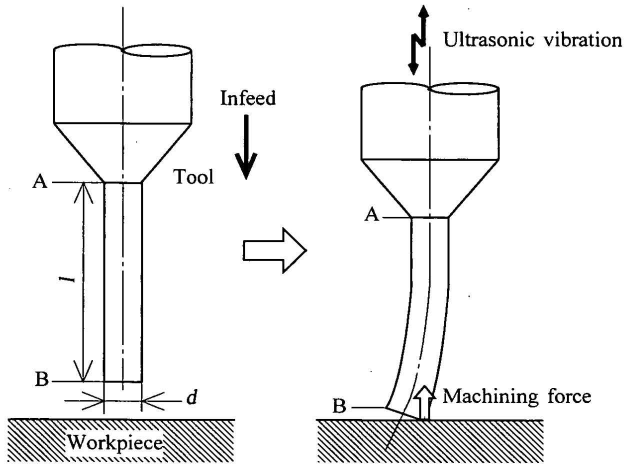
Here we consider a straight rod with diameter d and length l, as shown in Fig. 1(a). An axial compressive load is assumed to be acting on the rod during machining, where tool step A is the fixed end and point B in contact with the workpiece is the free end. For the conventional ultrasonic abrasive machining method, the optimum machining pressure is approximately 5 MPa or slightly lower[6]. If we assume that this condition also holds true for micro ultrasonic abrasive machining, the machining force in the axial direction is approximately 10 mN at a tool diameter d of 50 μm. If the tool is made of a tungsten carbide material, 10 mN is sufficiently small compared to the compressive breaking load of 12 N, and the buckling load of approximately 0.42 N (when $l=1$ mm); therefore, compressive fractures or buckling are very unlikely to occur as long as the tool is applied correctly.

However, tool wear remains a problem. If the tool is worn non-uniformly, as shown in Fig. 1(b), the tool will develop an asymmetric profile with respect to the tool axis (see Fig. 11(b), described later), generating non-uniform force components in the radial direction. The tool force in the radial direction due to asymmetric wear produces a force approaching the maximum bending strength at the tool step A, and this stress is likely to cause the tool to break when the stress exceeds the bending strength of the tool material (3.4 GPa for tungsten carbide in this experiment). The breakage load here is approximately 42 mN when $d=50$ μm and $l=1$ mm, which is significantly smaller than the buckling load described above. Non-uniform tool wear must therefore be minimized. In this study, the tool was rotated so as to achieve uniform wear of the tool edge.

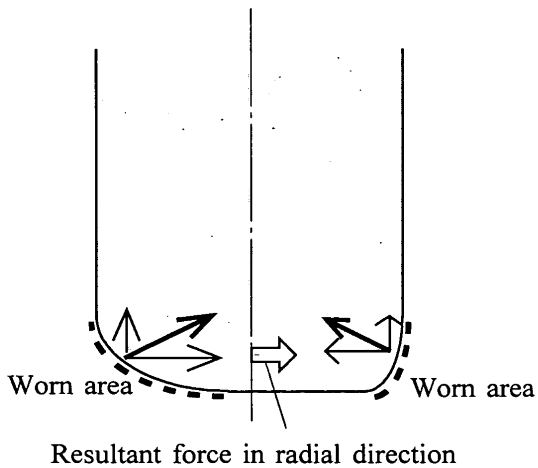
However, if the tool rotation is eccentric, resulting in only partial contact with the workpiece, an undesirable force in the tool radial direction will also be generated. Therefore, the tool rotation must have high rotation accuracy. In this study, we developed an ultrasonic vibration spindle supported by an aerostatic bearing, and minimized eccentricity due to tool mounting error by shaping the tool on the machine.

2.2 Mechanism of applying machining pressure

The two typical mechanisms for machining-force application used in conventional ultrasonic abrasive machining are hydraulic heavy bob and parallel-balance heavy bob. The former, in which the ultrasonic vibration head is fixed, is used in small machining systems, involving the application of upward pressure to the workpiece table by a hydraulic cylinder. In the



(a) Axial compressive load during machining



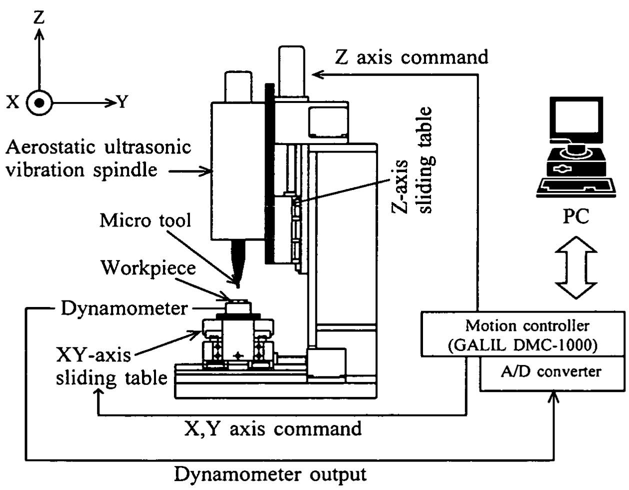
(b) Asymmetric wear profile

Fig. 1 Small-diameter tool

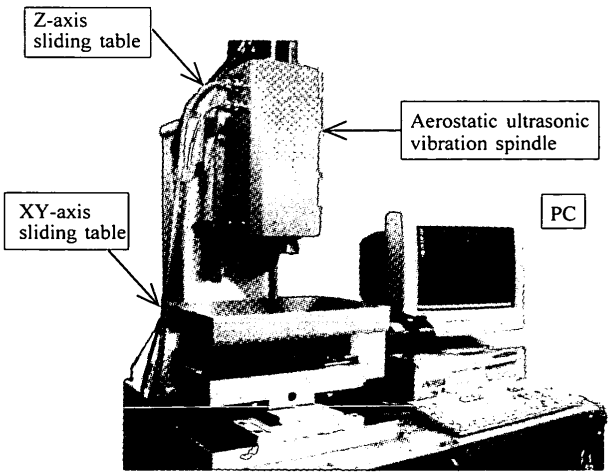
latter, used in large machining systems, the entire ultrasonic vibration head is balanced by the balancing mechanism and adds bob to apply pressure. The minimum settable machining force for both mechanisms is several hundred mN due to backlash of the running parts and sliding friction. In both cases, the machining force will easily exceed the buckling load of a small-diameter tool. In the present system, the machining force is constantly monitored using a dynamometer, and amount of infeed of the ultrasonic vibration head is controlled using the NC fine infeed mechanism so as to obtain constant machining force. This method allows any level of machining pressure to be set depending on the tool diameter, and also allows very small-force machining with improvement of the resolution of the dynamometer.

2.3 Supply of abrasive particle

At least one uniform layer of abrasive particles must be present between the tool and the workpiece throughout the machining process in order for machining to proceed. However, it has been found in previous studies[(7)-(10)] that air bubbles form between the tool and the workpiece due to cavitation produced by the ultrasonic vibration. These bubbles impede the supply of abrasive particles in the tool vicinity, thus preventing sufficient supply of abrasive particles from reaching the center of the tool. As the diameter of generated bubbles in micro ultrasonic abrasive machining with a small-diameter tool is significant, it is anticipated that the supply of abrasive particles may be completely inhibited, in the worst case resulting in no particles at the tool/workpiece interface and hence no machining. In the present system, the tool is rotated so as to stir the slurry between the tool and the workpiece, simultaneously eliminating bubbles and facilitating the supply of new abrasive particles.



(a) Schematic drawing of the system



(b) Photograph of whole view

Fig. 2 Micro ultrasonic abrasive machining system

3. Micro Ultrasonic Abrasive Machining System

3.1 Aerostatic ultrasonic vibration spindle

Based on the findings in the previous sections, a prototypal micro ultrasonic abrasive machining system was manufactured. A schematic and photograph of the equipment are shown in Fig. 2. The equipment consists of an aerostatic ultrasonic vibration spindle (hereinafter referred to as an ultrasonic head), a three-axis NC sliding table for three-dimensional movement of the small-diameter tool mounted on the head, a dynamometer for monitoring the machining force, and an ultrasonic torsional-vibration grinding unit for on-machine shaping of the tool. The equipment is constructed such that the ultrasonic head is fed vertically by the sliding table (Z-axis), which is driven by ball screws and an AC servomotor.

The structure of the ultrasonic head is shown in Fig. 3. Here, the aerostatic bearing supports the entire vibrator unit, which consists of a Langevin-type vibrator, cone and hone. Rotation is produced by the DC servomotor via a rubber coupling. The vibrator is supplied with power (rated output is 25 W) from the slip ring attached to the coupling. The tool is securely fastened and fixed using the collet chuck at the tip of the hone. The vibration characteristics at the tip of the hone were measured using an optical non-contact displacement meter (MTI-1000 manufactured by MTI; response frequency 80 kHz).

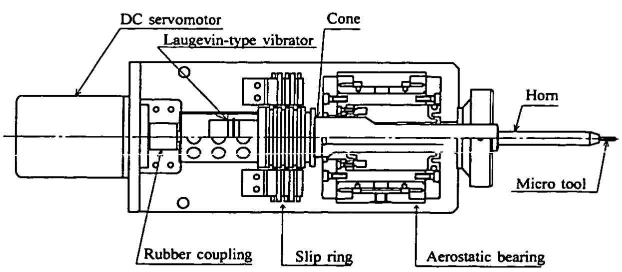


Fig. 3 Aerostatic ultrasonic vibration spindle

According to the measurement, the vibrator frequency is 25 kHz and the maximum amplitude at the tip of the hone is 20 μm p-p. The holding rigidity of the aerostatic bearing is 21 N/μm in the radial direction and 39 N/μm in the axial direction. The maximum rotation speed is 1000 rpm, with a run-out of 0.7 μm at the axis end. The three axes were simultaneously numerically controlled using a PC-based motion controller (DMC-1000, GALIL), with a minimum infeed resolution of 0.25 μm and an infeed speed of 0.5 μm/s to 2.0 mm/s.

3.2 Machining pressure control

The system was designed such that the machining force can be constantly monitored by the dynamometer attached to the XY-stage in order to control tool infeed numerically using the computer and hence maintain a constant machining force. When the minimum set machining force was 100 mN or larger, a small piezoelectric dynamometer was used (9256A2, manufactured by Kistler; maximum allowable load is 50 N, natural frequency is 6.4 kHz, and rigidity is 80 N/μm). Accurate measurement by the piezoelectric dynamometer was impossible at minimum set machining force of less than 100 mN due to drift and noise. Therefore, under low machining force conditions, a double-beam strain gauge dynamometer (LC4001, manufactured by A & D) with a resolution of 0.1 mN, a maximum allowable load of 1.2 N, a natural frequency of 51 Hz (measured value), and a rigidity of 4.52 mN/μm (measured value), was used instead. The machining force was measured every 10 ms at total of 50 times, and the average of these measurements was used for machining pressure control.

The changes in machining force under constant pressure control via tool feed control were examined in order to verify the accuracy of the control system. The dynamometer was initially loaded with a 5-g weight, and the tool was fed gradually, ensuring that the entire load was maintained at 6 gf (58.8 mN). The weight was then removed, and infeed motion was continued so as to maintain a load of 6 gf (set load). Figure 4 shows the depth of cut and the changes in dynamometer output (LC4001). Although the dynamometer exhibited approximately 3.9 mN of variation in the output, the control system was considered to be sufficiently accurate for this experiment. Furthermore, the system was designed to draw back the tool automatically and make an emergency stop when a sudden increase in the machining force was detected.

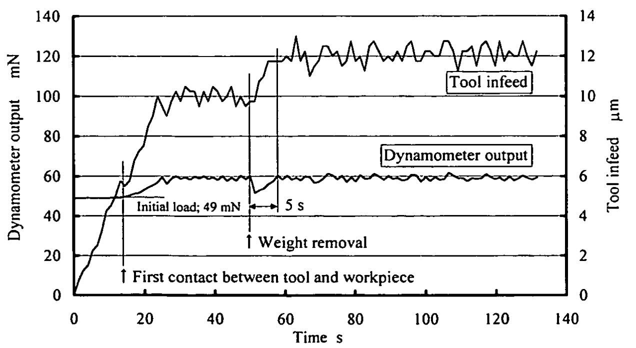


Fig. 4 Dynamic response of machining pressure control

3.3 On-machine shaping of small-diameter tool

In this experiment, ultra-fine-particle tungsten-carbide alloy (EM-10, manufactured by Toshiba Tungaloy; $\phi 1 \times 20$) was used for the tool. The tool was shaped as shown in Fig. 5. The cylindrical surface of a tungsten carbide rod fixed to the tip of the ultrasonic head was ground using the side of the diamond wheel. Torsional ultrasonic vibration was applied to the diamond wheel in order to grind the tool to a narrower diameter, as the application of such vibration has been shown to reduce the grinding force[6]. A schematic diagram of the on-machine tool

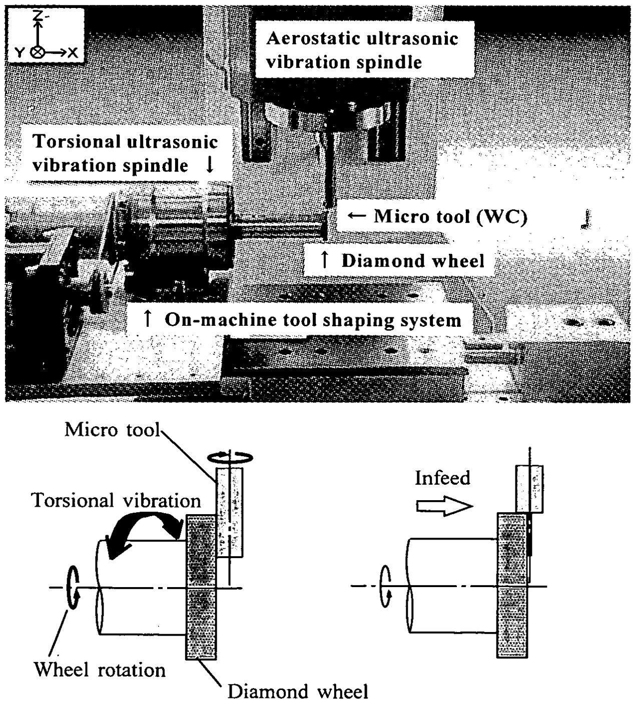


Fig. 5 On-machine shaping of small-diameter tool

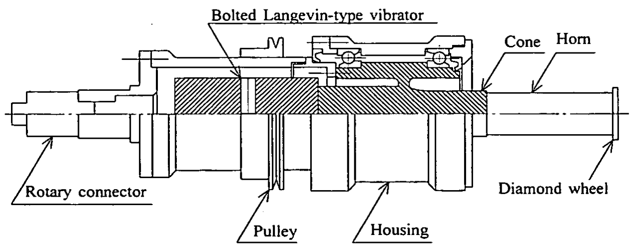


Fig. 6 Torsional ultrasonic vibration spindle for on-machine tool shaping

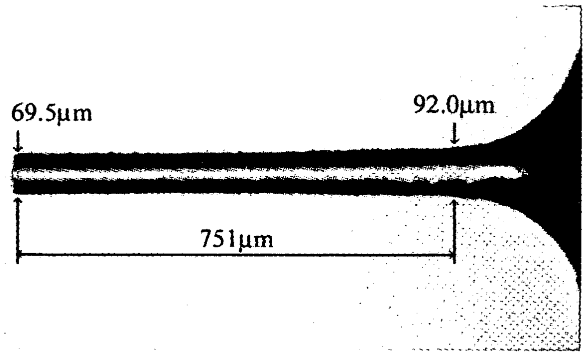


Fig. 7　Shaped tungsten carbide tool

shaping system is shown in Fig. 6. The bolted Langevin-type vibrator generates torsional vibration, which is amplified by the hone and cone before being transmitted to the diamond wheel at the tip of the hone. The ultrasonic torsional vibrator has an oscillation frequency of 18.5 kHz and a maximum output of 50 W, with a maximum amplitude of approximately 14 μm when measured on the circumferential surface of the 30 mm-diameter wheel.

A typical shaped tool is shown in Fig. 7. The small-diameter tool is not a straight cylinder, instead it is slightly tapered. A minimum 33 μm-diameter tool was obtained using this system. The grinding characteristics of small-diameter tools fabrication with torsional ultrasonic vibration will be described in detail in the next report.

4. Machining Experiments

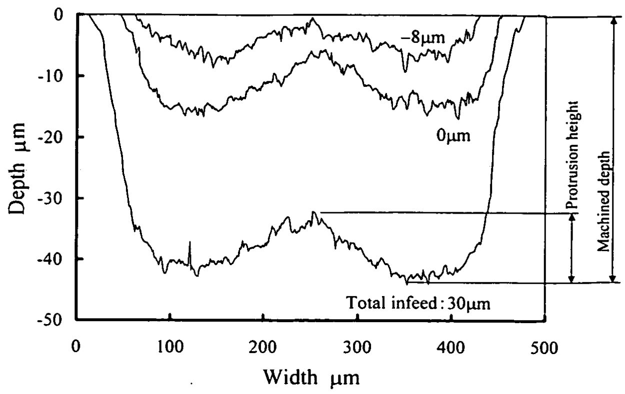
4.1 Experiment procedure

The dynamometer was installed on the XY-stage of the prototyped micro ultrasonic abrasive machining system, and a tray was fitted on the dynamometer. A glass workpiece was fixed in the tray, submerged in the slurry, and machined. The slurry was a prepared blend of 20% GC # 2000 by weight with tap water. A centrifugal mixing and defoaming system was used to remove microscopic air bubbles from the slurry and blend the abrasive particles uniformly. Although commonly used for conventional ultrasonic abrasive machining, a nozzle was not used for slurry supply and circulation as this method precludes accurate measurement of the machining force. In this case, the slurry was agitated by aerating the slurry in the machining area periodically using a superfine nozzle.

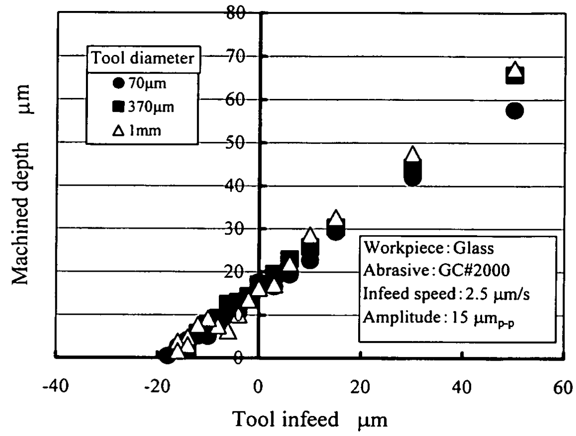
Although the target application of this system is the fabrication of three-dimensional shapes containing grooves and holes, in this study we conducted a simple drilling experiment in order to clarify the basic machining characteristics of the system.

4.2 Drilling process

The non-vibrating tool was gradually brought close to the workpiece while monitoring the output from the dynamometer to determine the point of contact (zero depth of cut). The tool was then temporarily drawn away in order to allow the slurry to flow into the machining area, and then constant-pressure machining was performed. Initially, the tool was applied without rotation in order to assess the effect of tool rotation. Figure 8(a) shows the change of the cross-sectional profile in drilling. Although there is topographical variation in the base of the hole profile, the machined depth was taken as the distance between the workpiece surface and the deepest point in the hole. Figure 8(b) shows the relationship between tool infeed and machined depth. It is apparent from the figure that material removal begins before the tool actually comes into a contact with the workpiece. The tool position here was −20 to −17 μm in almost all cases, regardless of tool diameter. From the vibrational amplitude (15 μm p-p), the average diameter of abrasive particles (at approximately 8 μm), and the vertical vibration of the tool tip with respect to the center non-vibrating position, it is considered that a single layer of abrasive particles was likely to be



(a) Change of cross-sectional profile



(b) Relationship between tool infeed and machined depth

Fig. 8　Drilling process

present between the tool end surface and workpiece at all times. Figure 9 shows a photograph of holes created using a 79 μm-diameter tool. Similar to the above, a single layer of abrasive particles was likely to be present between the tool side surface and workpiece at all times because the inside diameter of the hole is 105 μm.

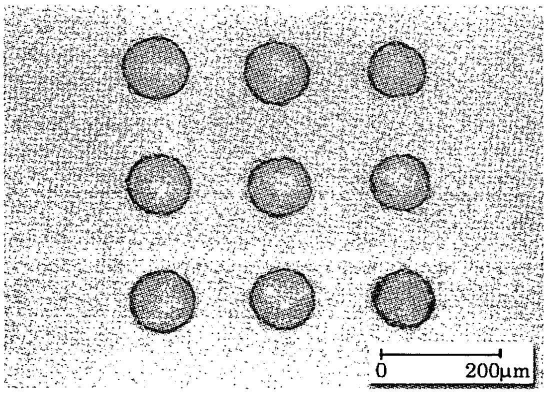
4.3 Influence of tool diameter

Micro tools of 80, 160, 470, and 730 μm in diameter were prepared, and the influence of tool diameter on machining characteristics was examined. The machining conditions were as follows: vibrational amplitude 15 μm p-p, abrasive particles GC # 2000, and machining pressure 2 MPa. Figures 10(a) and 10(b) show the influence of tool diameter on machining speed (change in machined depth with time) and tool wear, respectively. These figures illustrate that the machining speed of smaller-diameter tools is lower, particularly for the 80 and 160 μm-diameter tools. The tool wear was particularly long for the tool of diameter 80 μm. Figure 11 shows a microphotograph of the tips of the 80 and 730 μm-diameter tools. The edges of both tools were rounded due to wear. The rounded part of the edge of the 80 μm-diameter tool is relatively large compared to the tool diameter, resulting in a virtually spherical tool tip without the flat region that can be seen across the tip of the 730 μm-diameter tool. This probably caused the abrasive particles to be repelled toward the tool sides easily, preventing effective machining. As a result, the tool wear increased, decreasing the machining speed. This issue requires further investigation regarding the selection of appropriate abrasive particle diameters for the diameter of the tools used.

4.4 Effect of tool rotation

As is clear from Fig. 8(a), a rise is left in the center of the hole. Such protrusions were not observed for small-diameter tools (80 or 160 μm). This may be because the wear at the tool tip effectively removes the flat section at the tool tip, as described above. However, this means that even small-diameter tools produce cavitation, which has a significant effect on the machining process.

The change in protrusion height with the progress of machining was examined for various rotation speeds using the 370 μm-diameter tool. The result is shown in Fig. 12. The protrusion height tended to increase with machining time. However, the protrusion height and the rate of increase reduced when the tool was rotated. In particular, at the rotation speed



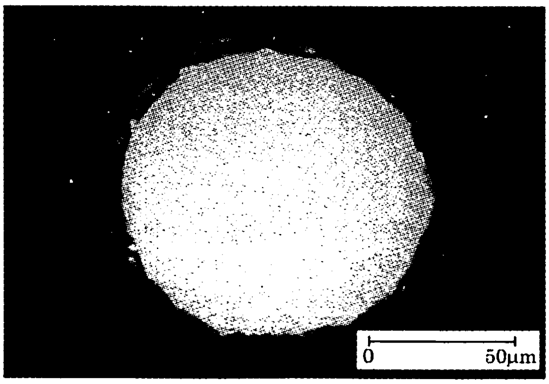
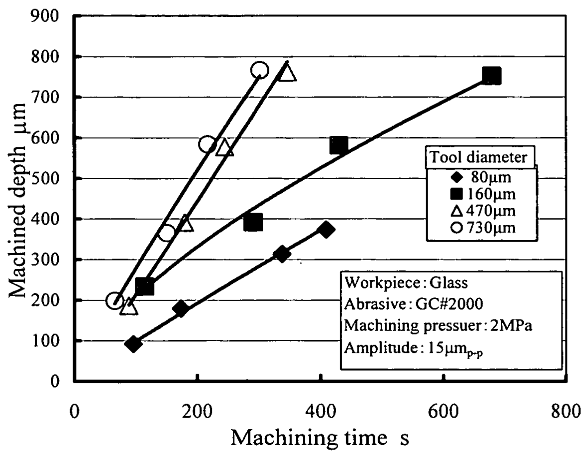
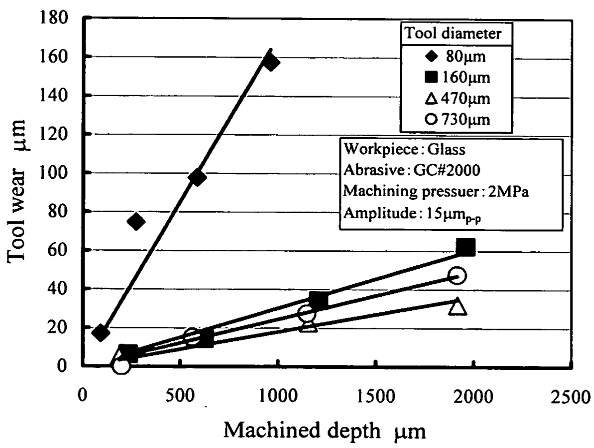


Fig. 9 Micro holes

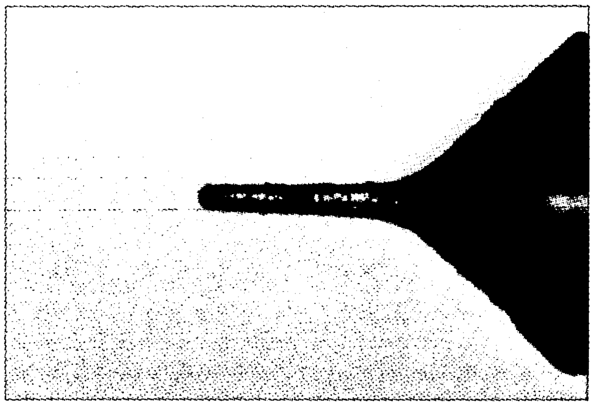


(a) Change in machined depth with time



(b) Tool wear

Fig. 10 Influence of tool diameter



(a) Tool diameter 80 μm

(b) Tool diameter 730 μm

Fig. 11 Wear of tool tip

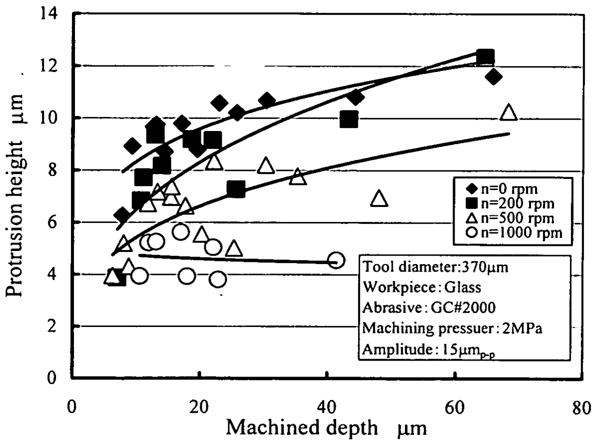
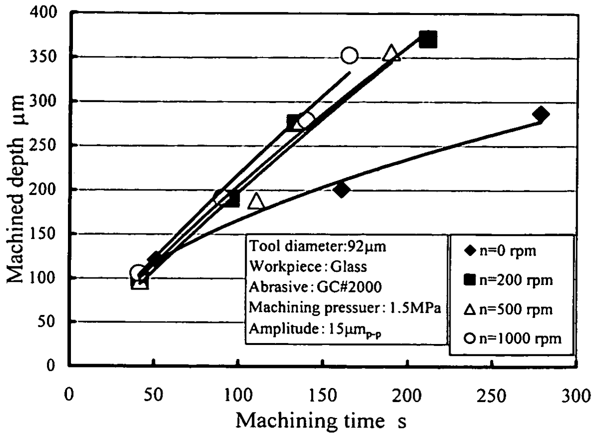
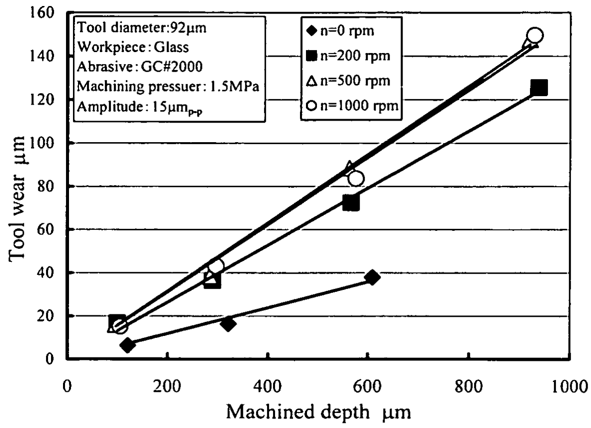


Fig. 12 Change in protrusion height with time



(a) Change in machined depth with time



(b) Tool wear

Fig. 13 Influence of tool rotation

of 1000 rpm, the protrusion height remained virtually constant throughout the machining process without increase. Specifically, it was found that the protrusion height could be reduced to less than half the normal protrusion height by rotating the tool.

Figure 13 shows the influence of tool rotation on the machining speed and tool wear. When the tool was rotated, both the machining speed and tool wear increased. Moreover, rotating the tool approximately doubled the machining speed, and the machining speed did not decrease over time, whereas the machining speed decreases with the progress of machining when the tool is not rotated. This effect was found to be largely independent of the tool rotation speed; simply rotating the tool produced this effect. The cross-sectional profile of the worn tool became axisymmetric, as expected.

As described above, it has been found that rotating the tool not only decreases the severity of protrusions along the machining path, but also improves machining speed.

5. Conclusions

A micro ultrasonic abrasive machining system was developed as one method of micro mechanical fabrications of micro-sized holes, slits and 3D structures. Micro-holes were machined in glass, and basic machining characteristics including the influence of tool diameter and tool rotation were investigated. The findings of the investigation are as follows:

(1) The prototypal machining system was manufactured, which has an aerostatic ultrasonic vibration spindle, 3-axis NC sliding tables, dynamometer for machining pressure control and on-machine shaping system for small-diameter tools.

(2) As the tool diameter becomes smaller, the machining speed becomes lower and tool wear increased.

(3) Protrusion is left in the center of the machined hole using the tool of 370 μm-diameter or more over, the protrusion height tended to increase with machining time.

(4) Protrusion height and the rate of increase reduced when the tool was rotated. At the rotation speed of 1000 rpm, the protrusion height was reduced to less than half the protrusion height without tool rotation, and remained virtually constant throughout the machining process without increase.

(5) Rotating the tool approximately doubled the machining speed, and the machining speed did not decrease over time.

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