https://doi.org/10.20965/ijat.2013.p0278

Paper:

Applying Constant Pressure Unit to Ductile Mode Cutting of Hard and Brittle Materials

Kunitaka Kuriyama*, Masahiko Fukuta*, Katsuhiko Sekiya, Keiji Yamada**, and Yasuo Yamane****

*Toshiba Machine Co., Ltd.
2068-3 Ooka, Numazu, Shizuoka 410-8510, Japan
E-mail: kuriyama.kunitaka@toshiba-machine.co.jp
**Graduate School of Engineering, Hiroshima University
1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan
[Received November 1, 2012; accepted January 25, 2013]

It is strongly wished that hard and brittle materials could be used in a wide variety of fields because of their great material characteristics. For now, however, minute profiling or high-efficiency cutting of these materials has not yet been put into practice due to their hardness. At the same time, there have been numerous reports available on ductile mode cutting for hard and brittle materials in response to the increasing demand. Very smoothly finished surfaces can reportedly be generated through the work of a material removal mechanism similar to plastic deformation, done by microminiaturizing cutting units with the sharp cutting edges of tools. Because of the extremely narrow ductile mode regions, however, forced cutting processing, which includes cutting work, demands extremely high motion performance or rigidity of machine tools, and this makes it difficult to realize stable ductile mode cutting. On the other hand, pressure cutting processing similar to polishing is known to be capable of producing extremely smooth finished surfaces on hard and brittle materials; this suggests that we could realize stable ductile mode cutting that will always create the same depths of cut by controlling the insertion forces on the tools. In this paper, in order to realize stable ductile mode cutting, we have devised and prototyped a constant pressure cutting device which can regulate cutting forces by regulating supply pressure with air static pressure bearings. We have investigated the relationships between the pressure supplied in the cutting direction and the cutting forces in order to get static pressure characteristics of the prototype device. We have also carried out experiments to cut hard and brittle materials with the prototype constant pressure cutting device mounted on the tool post of an ultra-precision machine tool to prove the effectiveness of the constant pressure cutting device for the ductile mode cutting of hard and brittle materials.

Keywords: hard and brittle materials, ductile mode cutting, constant pressure cutting, microstructure, critical depth of cut

1. Preface

Technologies related to optical electronics and semiconductor devices have seen rapid developments in recent years, and such devices have required far more accurate, more miniaturized, and more multifunctional components. In other words, these devices have needed to be high-value-added. On the other hand, hard and brittle materials, such as glass and silicon carbide (SiC), are used in a wide variety of fields. This is because of their great material characteristics in terms of hardness and optical characteristics as well as their material homogeneity, as these are the most important characteristics for nanofabrication. These hard and brittle materials, very difficult to cut as work materials, have been produced by polishing processing or deposition processing rather than by minute profiling or high-efficiency processing. On the other hand, there are many research studies underway in an effort to extend the range of applications of ultra-precision processing, and there have been many cases reported in which ductile mode cutting with monocrystalline diamond tools has been applied to various hard and brittle materials [1]. Those studies have verified that smoothly-finished surfaces with no brittle damage on hard and brittle materials can be created by microminiaturizing the processing units with the sharp cutting edges of tools and that material removal mechanism in the cutting mode was based on plastic deformation [2]. Some studies have reported on the depths of cut in the ductile-brittle transition of various hard and brittle materials, called critical depths of cut (dc), as obtained in many different cutting conditions [3]. In those reports on dc, the authors have obtained the depths of cut by first cutting into work materials in an oblique direction with the tool's cutting edges and then by identifying the ductile cutting regions and the brittle transition points through observation of the worked surfaces. Any profiling would require extremely narrow regions for critical depths of cut to be maintained throughout the cutting processes. The lack of a sufficient number of machine tools with the level of motion performance that will meet the abovementioned requirements makes it difficult to put into practice minute profiling or high-efficiency processing for hard and brittle materials [4]. As an example of the cutting of hard and brittle materials using elliptical oscillation, there is another work that reports that fine-finished surfaces have been obtained by adding elliptical oscillations to the cutting motions of tools [5]. It is also reported therein that the cutting tools get worn out very rapidly, providing another problem to be solved before such cutting methods are put into practice. There have also been some other reports [6, 7] of the successful cutting of hard and brittle materials in the ductile mode with rotary tools. These tools make use of the advantage of rotary tools, namely that their cutting edges can make small depths of cut. Even with such rotary tools, however, we cannot do any profiling that is smaller than the rotation curvatures of the rotary tools, and this makes it difficult to apply such rotary tools to minute profiling.

2. Classification of Machining

Machining is largely classified into forced cutting and pressure cutting. In cutting and polishing processing, both of which are classified as forced cutting, the cutting edge of a tool is first positioned, via the position control mechanism of the machine tool, on the coordinates of preset depths of cut for work materials. Relative motions are then started between the tool and the work material by means of the motion mechanism of the machine tool. The quantities to be removed by cutting are determined by preset depths of cut and feed rates to achieve very high-efficiency cutting. With tools and work materials completely held in the machine tool, however, the static and dynamic accuracies of the machine tool itself are bound to directly affect its cutting accuracies; its motion accuracies are directly reflected in the accuracies of the work material being cut.

On the other hand, in pressure cutting, which falls into the category of abrasive cutting, tools are inserted into work materials by means of applied pressure. As tools represent floating abrasive grains, their cutting accuracies are not so susceptible to the motion accuracies of the machine tool that they would be determined by the accuracies of the worked surfaces of the work materials. As cutting progresses, the accuracies of worked surfaces and the guidance of tools are both so improved that the worked surfaces result in very accurate shapes. However, cutting efficiency gets lowered because forces delivered to one abrasive grain are so small that only shallow cuts can be made. On top of that, pressure cutting has the disadvantage of not being able to be applied to minute profiling because it cannot properly control the positions of working points of the floating abrasive grains which serve as the tool. In this paper, noting that mirror finishes can be achieved by polishing hard and brittle materials [8] but not by cutting them, we propose a cutting method which make possible to control depths of cut and the positions of the tool's cutting edge so stable that they will not be affected by the motion performance of the machine. In this study, we have devised and prototyped a constant pressure cutting device that has air static pressure bearings mounted in three directions so that constant pressure cutting can be applied to hard and brittle materials. The outline of the prototype constant pressure cutting device is illustrated in **Fig. 1**. It is constructed so that a slider with a tool holder mounted at the forward end is retained by a radial air static pressure bearing and two thrust air static pressure bearings fore and aft. Consequently, forces that insert the tools into the workpiece can be regulated by any difference in the pressure of air supplied to the fore and aft thrust bearings. Air pressure supplied to the air static pressure bearings can be regulated with a regulator via a digital pressure gauge, and displacements of the tool can be directly measured with a laser interference measurement sensor, which has minimum resolutions of 8.4 nm, installed at the back end of the slider.

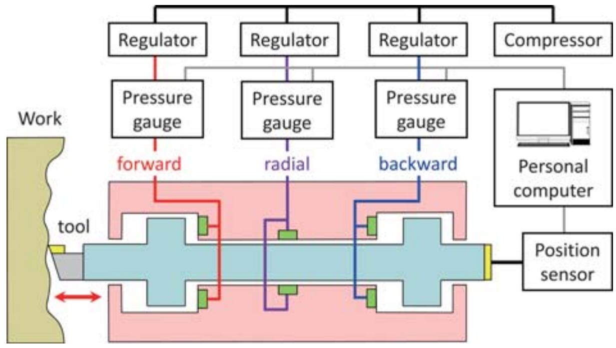

Fig. 1. Schematic view of constant pressure unit.

3. Static Characteristics of Constant Pressure Cutting Device

The constant pressure cutting device used in this study has a difference in bearing clearances in the radial direction and axial directions so that it can make strokes in the longitudinal direction. On top of this, circuits within the static pressure bearings are not independent of each other, which cause pressure fluctuations. For these reasons, it may not be possible for the device to sustain constant pressure cutting conditions. In order to check whether the device can actually perform constant pressure cutting, therefore, we have measured its insertion forces caused by the restoration forces of a flat spring. **Fig. 2** is an outline drawing of the experiments. For the experiments, we installed the constant pressure cutting device on the tool post and a CCD camera on the Z-axis of the machine tool in order to observe the contact conditions of the flat spring. We have slowly inserted, by means of the flat spring, a pin fitted at the forward end of the constant pressure cutting device to measure and record the displacements of the flat spring, the machine coordinates of the ultra-precision machine tool, and the movements of the pin in relation to the constant pressure cutting device. **Fig. 3** illustrates the ideal relationships between the Z-axial displacements and the pin's insertions; the Z-axial displacements and the pin's insertions are each set at 0

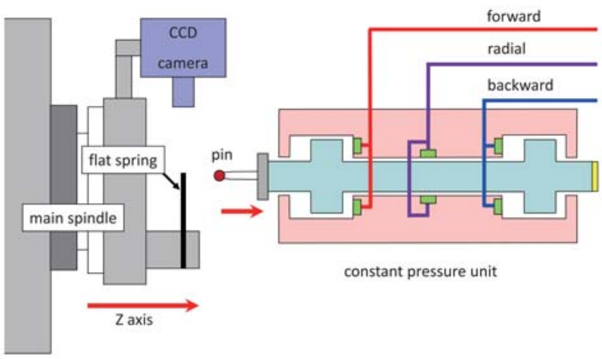

Fig. 2. Measuring test of insertion force.

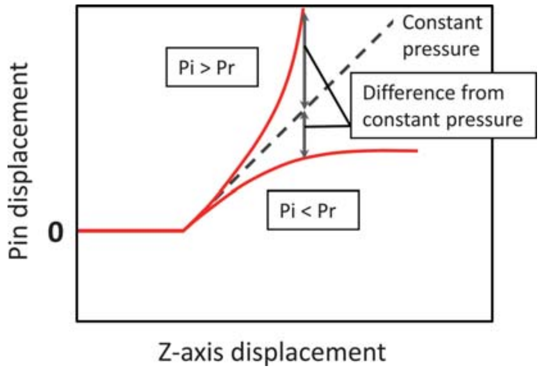

Fig. 4. Non-constant pressure condition.

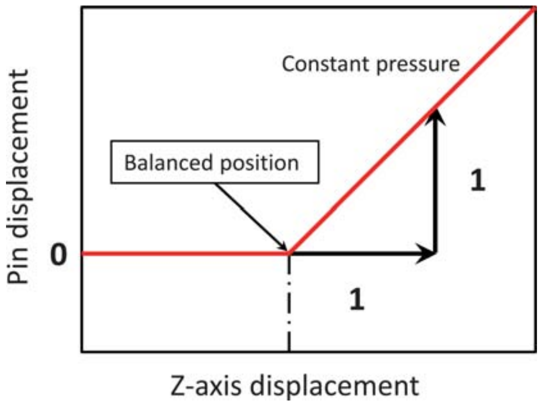

Fig. 3. Constant pressure condition.

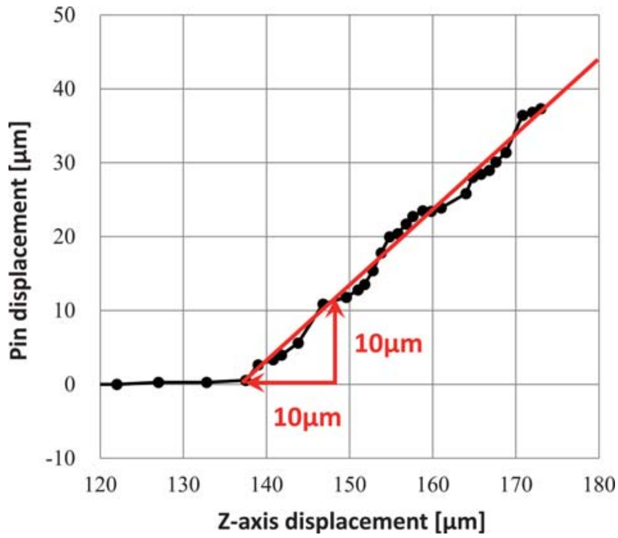

Fig. 5. Measuring test of insertion force.

when they are in contact. When the pin with insertion forces Pi is inserted by the flat spring, the flat spring undergoes a deflection to create restoration forces Pr. When displacements of the flat spring are small and insertion forces of the pin are large, i.e., $Pr < Pi$, the Z-axial displacements of the machine tool on the insertion side only increase without any movements of the pin. Increases in the Z-axial displacements only with no movements of the pin indicate that the flat spring has thus been displaced. When the restoration forces of the flat spring Pr balance the insertion forces of the pin Pi as the Z-axial displacements increase, i.e., $Pr = Pi$, the pin is inserted as the Z-axial displacements increase. In this case, the Z-axial incremental displacements and insertions of the pin are equal and the inclination of the graph in **Fig. 3** becomes 1. The inclination 1 indicates that restoration forces Pr of the flat spring and insertion forces of the pin Pi are constantly in balance or that the proposed device is in a state of constant-load cutting operation. We can also tell from **Fig. 3** that the Z-axial displacements or any difference in displacements between the Z-axis and the pin when the inclination of the graph begins to change represent displacements of the flat spring. If the proposed device is not under constant pressure conditions, we can change the forces to insert the pin by changing the positions in which the tool is held. In such a case, the graph does not present a straight line of inclination 1; when insertion forces Pi are smaller, the curve will come below that for the constant pressure conditions, and when insertion forces Pi are larger, the curve will come above that for the constant pressure conditions, as shown in **Fig. 4**.

Figure 5 illustrates the relationships between the Z-axial displacements and the pin's insertions when a flat spring 0.02 mm in thickness is used, when the pressure of the radial bearing is 0.538 MPa, and when the difference in pressure between the forward and aft thrust bearings is 0.240 MPa. The graph in **Fig. 5** shows that the pin is not inserted until the Z-axial displacements approach 138 μm. This indicates that displacements of the flat spring are so small that the forces to insert the pin are larger than the restoration forces of the flat spring. Further insertion of the Z-axis has resulted in a straight line of inclination 1. The pin seems to be inserted by the number of incremental displacements of the Z-axis. The foregoing proves that constant pressure cutting is feasible with the proposed device.

4. Experimental Equipment and Methods

With the constant pressure cutting device installed on the tool post of an ultra-precision lathe, we have con-

Fig. 6. General overview of ultra-precision machine tool.

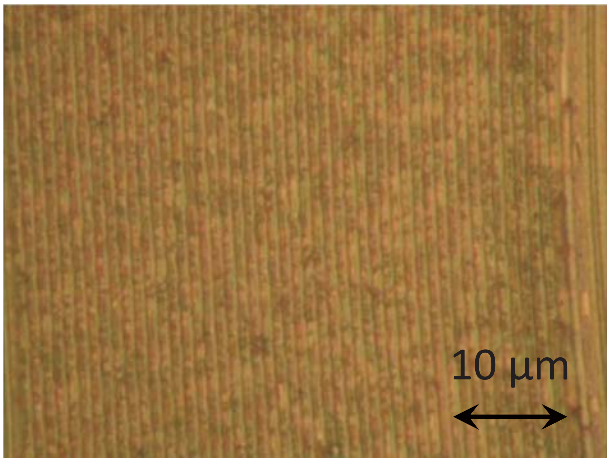

Fig. 7. Microscopic image of electro-less nickel plating.

Table 1. Cutting conditions.

Tool	monocrystalline diamond		
Work material	Electro-less nickel plating	CVD-SiC	Optical glass
Insertion force	4.0 mN		1.6 mN
Spindle rotation	10 min^{-1}		
Feed rate	1 μ/rev		

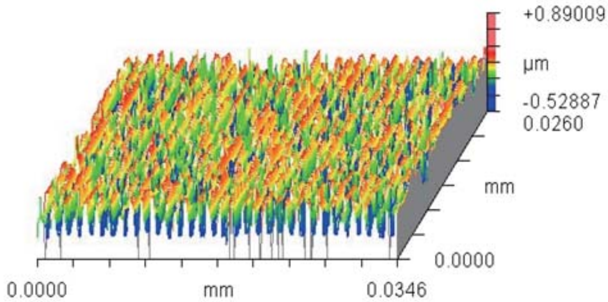

Fig. 8. Cross-sectional image of electro-less nickel plating.

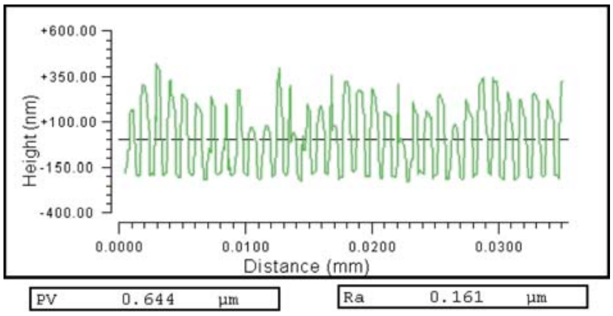

Fig. 9. Cross-sectional profile of V-groove of electro-less nickel plating.

ducted experiments to cut electro-less nickel plating, CVD-SiC, and optical glass. The ultra-precision machine tool has highly accurate aero static bearing on the work spindle and an ultra-precision V-V rolling guide on each axis, enabling high-accuracy cutting in units of 10 nm.

Figure 6 is an overview of the machine tool. Cutting conditions are given in **Table 1**. We have used monocrystalline diamond tools with an apex angle of 60° and rake angle of 0° to cut electro-less nickel plating and CVD-SiC. We have used monocrystalline diamond tools with an apex angle of 90° and rake angle of 0° to cut optical glass, in continuous V-grooves at a pitch of 1 μm, through the use of front lathe turning. We have set the cutting forces for electro-less nickel plating and CVD-SiC at 4.0 mN and those for optical glass at 1.6 mN. We have set the revolutions of the main axis at 10 rpm, the lowest revolutions in the specifications of the machine tool. In this study, we did not carry out any pre-processing of work materials once they were installed on the ultra-precision machine tool, so the cutting experiments were conducted with work materials in uncoordinated surface shapes. The finished surfaces have been observed with a differential interference microscope and a three-dimensional surface texture measurement device.

5. Results and Consideration

Figure 7 shows differential interference microscopic pictures of the finished surfaces of electro-less nickel plating as obtained by the V-groove cutting. Observed on the finished surfaces are uniform, continuous V-grooves that are synchronized with a feed rate of 1 μm/rev, but there is no chipping or other defects. This seems to be evidence of proper ductile mode cutting.

Figure 8 presents the surface texture measurement results. It shows very sharp troughs of nearly equal depths; this means that stable V-grooves have been created by the deeply inserted tool throughout the cutting period. Wavy surface components seem to have resulted from the tool that cuts along the prior shapes in the constant pressure cutting processes.

Figure 9 shows cross-sectional profiles of the electro-less nickel plating cut using the constant pressure cutting method. The P-V value is 644 nm, a little less than the theoretical roughness of 866 nm. The cross-sectional profiles show comparatively sharp peaks at higher points and

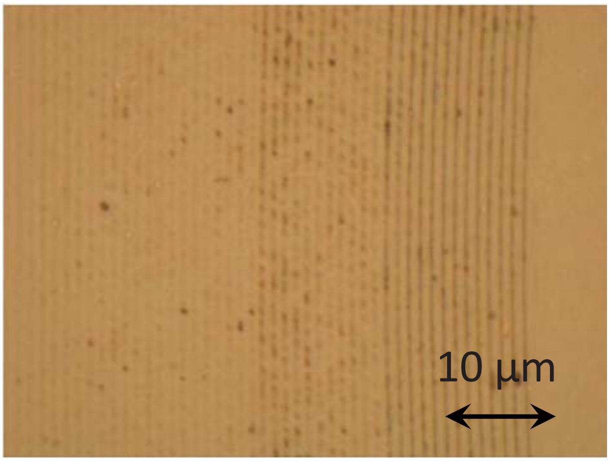

Fig. 10. Microscopic image of CVD-SiC.

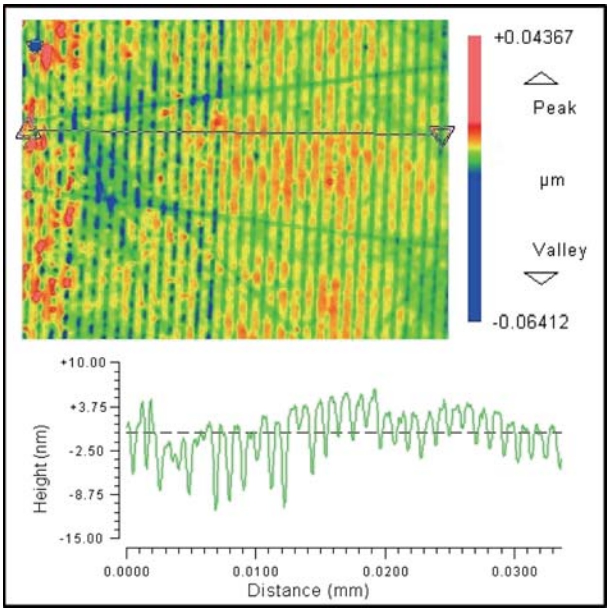

Fig. 11. Cross-sectional profile of CVD-SiC.

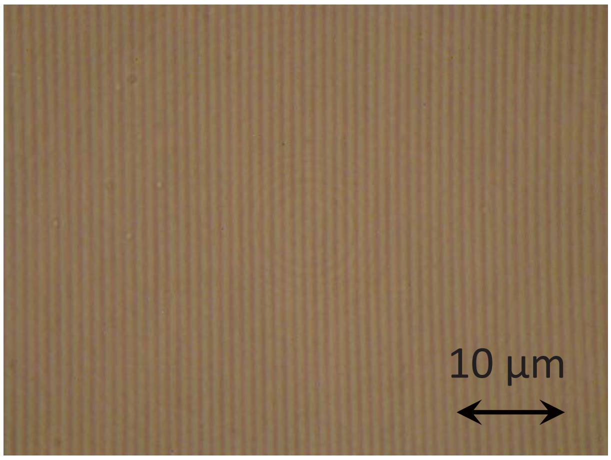

Fig. 12. Microscopic image of optical glass.

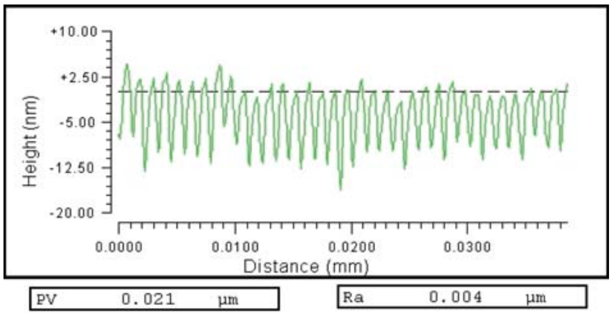

Fig. 13. Cross-sectional profile of V-groove of optical glass.

some marks of broken surfaces in one direction at lower points. Given that some geometric shapes cutting along the prior shapes are transcribed in the troughs, it seems that the steep peaks generated immediately after cutting have been cracked and broken by kind of stress concentration from the prior grooves. The foregoing indicates that constant pressure cutting can be applied to electro-less nickel plating with a cutting force of several mN, regardless of constant depths of cut.

Figure 10 shows differential interference microscopic pictures of the finished surfaces of CVD-SiC as cut in V-grooves. Although we can observe uniform, continuous V-grooves with a pitch of 1 μm, the prior shapes have such strong effects on them that some grooves are clear while others are unclear. **Fig. 11** illustrates the cross-sectional profiles for **Fig. 10**. In some regions, the grooves created have depths of about 10 nm, while in other regions the grooves are about 7 nm deep, or a few percent of those for the worked surfaces of electro-less nickel plating. No brittle fracture marks are observed in the cutting direction. This is evidence that ductile mode cutting can be applied to CVD-SiC, too, with a cutting force of several mN. Smaller depths of grooves in CVC-SiC than those in electro-less nickel plating are due to a large difference in hardness between them; with hard work materials, the depths of cut that balance with cutting forces are so shallow that cutting is done with only the tip of the cutting edge. This results in groove depths much shallower than the theoretical roughness.

Figure 12 shows the differential interference microscopic pictures of the finished surfaces of optical glass as cut in V-grooves. There is no chipping or other defects observed on the finished surfaces, where uniform grooves have been created at a pitch of 1 μm. **Fig. 13** illustrates the cross-sectional profiles as obtained from the surface texture measurements for **Fig. 12**. Despite the belief that critical depths of cut for optical glass should be about 25 nm owing to its low fracture toughness [9, 10], actual grooves created on the finished surfaces are no more than about 20 nm. Although that leaves as little tolerance as 5 nm in the depths of cut before the optical glass transitions to the brittle mode, absolutely no brittle fracture marks are observed on the worked surfaces. This seems to suggest that ductile mode cutting has taken place throughout the cutting processes and that the constant pressure cutting device has produced very stable working conditions. This proves that constant pressure cutting can properly be applied to optical glass as well, with a cutting force of several mN realizing stable ductile mode cutting. Constant pressure cutting in the ductile mode can be applied to hard and brittle materials in general, although we need to further ascertain the cutting conditions under which stable ductile mode cutting could be sustained, irrespective of any differences in material characteristics.

6. Conclusion

In this study, in order to realize stable ductile mode cutting for hard and brittle materials, we have devised and prototyped a constant pressure cutting device with air static pressure bearings mounted. We have conducted experiments to cut various hard and brittle materials at constant pressure after investigating the static characteristics of the prototyped device. The following are the conclusions we have reached:

1. The prototyped constant pressure cutting device has been found capable of sustaining constant cutting forces.
2. Cutting forces can be controlled by combining the pressure of the three air static pressure bearings.
3. The constant pressure cutting device has been found capable of cutting in ductile mode with constant depth of cut along the prior shapes.
4. The constant pressure cutting device has been found capable of cutting electro-less nickel plating and optical glass in the ductile mode.
5. The constant pressure cutting device has also been found capable of cutting CVD-SiC in the ductile mode, creating V-grooves several nanometers in depth.

References:

[1] K. Kuriyama, M. Fukuta, and Y. Yamane, "Deterministic ultra-precision cutting of cemented carbide for aspheric mold," ICPMT, p. 353, 2006.
[2] Y. Ichida, N. Ben Frej, and R. Yousefi, "Ductile-mode mirror cutting of single crystal silicon," JSPE, Vol.64, No.4, 1998.
[3] Y. Kamimura, Y. Tani, H. Sato, and H. Yamaguchi, "Ductile Regime Cutting of Brittle Materials Using a Flying Tool Under Negative Pressure," JSME(C), Vol.63, No.614, pp. 3654-3659.
[4] K. Kuriyama, M. Fukuta, K. Sekiya, K. Yamada, and Y. Yamane, "Forming of microstructure on hard brittle materials in ductile mode cutting," ICoPE, 447-448, 91, 2010.
[5] N. Suzuki, S. Masuda, and E. Shamoto, "Ultraprecision machining of sintered tungsten carbide by applying ultrasonic elliptical vibration cutting," Proc. of 4th Int. Conf. and 6tth annual general meeting of ESPEN, 2004.
[6] Y. Yamamoto, H. Suzuki, H. Kawabata, T. Moriwaki, K. Fujii, Y. Goto, and T. Ono, "A study on ultra precision cutting of micro aspherical molds of tungsten carbide with PCD milling tools," JSME, Vol.34, No.6, p. 179, 2006.
[7] T. Iizuka, "Ductile-mode cutting for glass," JSAT, Vol.52, No.11, p. 634, 2008.
[8] K. Ohtani, H. Okuyama, Y. Mori, K. Matsuoka, and Y. Yamasaki, "Fabrication of Aspherical Lens by Elastic Emission Machining," JSPE, Vol.57, No.1 pp. 85-90, 1991.
[9] T. Biffano and P. Bierden, "Fixed-abrasive grinding of brittle hard-disk substrates," IJMTM, Vol.37, Issue 7, pp. 935-946, 1997.
[10] I. Ogura and Y. Okazaki, "Ductile-regime machining of optical glasses by means of single point diamond turning," JSPE, Vol.66, No.9, p. 1431, 2000.

Name:
Kunitaka Kuriyama

Affiliation:
Nano Processing System Division, Toshiba Machine Co., Ltd.

Address:
2068-3 Ooka, Numazu, Shizuoka 410-8510, Japan
Brief Biographical History:
1999- Toshiba Machine Co., Ltd.
Main Works:
• Manufacturing of ultra-precision machine tool
Membership in Academic Societies:
• The Japan Society for Precision Engineering (JSPE)
• The Japan Society for Abrasive Technology (JSAT)

Name:
Masahiko Fukuta

Affiliation:
Nano Processing System Division, Toshiba Machine Co., Ltd.

Address:
2068-3 Ooka, Numazu, Shizuoka 410-8510, Japan
Brief Biographical History:
1998- Toshiba Machine Co., Ltd.
Main Works:
• Development of ultra-precision machining
Membership in Academic Societies:
• The Japan Society for Precision Engineering (JSPE)
• The Japan Society for Abrasive Technology (JSAT)

Name:
Kathuhiko Sekiya

Affiliation:
Assistant Professor, Graduate School of Engineering, Hiroshima University

Address:
1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan

Brief Biographical History:
1998- Hiroshima University

Main Works:
- "An Evaluation of Difficulty in Machining Difficult-to-Cut Materials by using Difficult to Cut Rataing," J. of the JSPE, Supplement. Contributed papers, Vol.70, pp. 407-411, Mar. 2004.
- "Tool Wear under High-Speed End Milling of Nickel-Based Superalloy Inconel 718," J. of the JSPE, Supplement. Contributed papers, Vol.70, pp. 1086-1090, Aug. 2004.
- "Evaluation of Adhesion on Tool-Chip Interface with Dynamic Components of Cutting Force," J. of the JSPE, Vol.76, pp. 926-932, Aug., 2010.

Membership in Academic Societies:
- Japan Society for Precision Engineering (JSPS)
- Japan Society of Mechanical Engineers (JSME)
- Japan Society for Abrasive Technology (JSAT)

Name:
Yasuo Yamane

Affiliation:
Professor, Graduate School of Engineering, Hiroshima University

Address:
1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan

Brief Biographical History:
1980- Lecturer, Hiroshima Denki Institute of Technology
1985- Associate Professor, Hiroshima University
1995- Professor, Hiroshima University

Main Works:
- "An Evaluation of Difficulty in Machining Difficult-to-Cut Materials by using Difficult to Cut Rataing," J. of the JSPE, Supplement. Contributed papers, Vol.70, pp. 407-411, Mar. 2004.
- "Evaluation of Adhesion on Tool-Chip Interface with Dynamic Components of Cutting Force," J. of the JSPE, Vol.76, pp. 926-932, Aug. 2010.
- "Metal machining – Theory and applications –," ARNOLD, 2000.

Membership in Academic Societies:
- The Japan Society for Precision Engineering (JSPE)
- The Japan Society of Mechanical Engineers (JSME)
- The Japan Society for Abrasive Technology (JSAT)

Name:
Keiji Yamada

Affiliation:
Associate Professor, Graduate School of Engineering, Hiroshima University

Address:
1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan

Brief Biographical History:
1992- Research Associate, Kanazawa University
2002- Lecturer, Kanazawa University
2005- Associate Professor, Hiroshima University

Main Works:
- "Temperature and Absorptivity of Workpiece in CO_2 Laser Processing," J. of the Japan Society of Precision Eng., Vol.65, Issue 1, pp. 126-130, 1999.
- "Thermal Stress Cleaving of Brittle Materials by Laser Beam," Annals of the CIRP, Vol.51, No.1, pp. 149-153, 2002.
- "Evaluation of Adhesion on Tool-Chip Interface with Dynamic Components of Cutting Force," J. of the Japan Society of Precision Eng., Vol.76, Issue 8, pp. 926-932, 2010.
- "A Study on Aspects of Attrition Wear of Cutting Grains in Grinding Process," Int. J. of Precision Engineering and Manufacturing, Vol.12, Issue 6, pp. 965-973, 2011.

Membership in Academic Societies:
- The Japan Society for Precision Engineering (JSPE)
- The Japan Society of Mechanical Engineers (JSME)
- Japan Laser Processing Society (JLPS)
- The Japan Society for Abrasive Technology (JSAT)