Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)
15–18 November 2022, Singapore. Edited by Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-12-0300

Aspheric Cutting of CVD-SiC Molds by PCD milling tool

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KEYWORDS: Polycrystalline diamond tool, CVD-SiC, Precision cutting, Milling, Wire EDM, Cutting force

Demands of large molded components with many types of structured surface are increasing in optical device and medical device. Furthermore, structured molds of harder ceramics are required to decrease the mold wear and increase a number of molding times. In order to machine large structured molds of CVD-SiC, large milling tools made of polycrystalline diamond (PCD) were developed. Three hundred cutting edges were generated sharply and precisely by wire EDM and grinding on the edge of a PCD wafer. In the fundamental cutting tests of three types of CVD-SiC with different grain sizes, micro grooves were machined by the developed PCD milling tool, and aspheric cutting tests were carried out. From the experimental results, it was clarified that the developed PCD milling tool was useful for high-efficiency and ultra-precision cutting of CVD-SiC.

1. Introduction

Demands are increasing for structured components to be installed in various optical devices, such as light systems for automobile, functional display panels, and anti-reflective panels. Most of the structured components are made of plastics, and generally mass produced by injection molding with machined molds made of harden steel. To increase the mold life, molds made of tungsten carbide or silicon carbide are required.

The dies and molds are mostly ground with micro diamond wheels. The diamond wheel must be trued carefully on the machine before grinding, however the grinding wheel wears soon, and it is difficult to keep the original geometrical shape of the wheel. It is, therefore expected that the ceramic dies and molds could be finished with high accuracy if a proper diamond cutting tool is developed as the size of the dies and molds becomes smaller and the required accuracy becomes higher. Shamoto and Moriwaki developed the ultrasonic elliptical vibration cutting method and applied to mirror machining of hard materials with single crystal diamond tool. In this cutting method, the materials are removed by interrupted cutting and the tool wear can be decreased. It is therefore expected that the hard tungsten carbide and silicon carbide can be cut with micro milling tool.

2. Development of milling tool

The PCD milling tool was fabricated as shown in Fig. 1. At first the PCD wafer was bonded with a silver alloy on to a cemented carbide

Fig. 1 Machining process of PCD milling tool

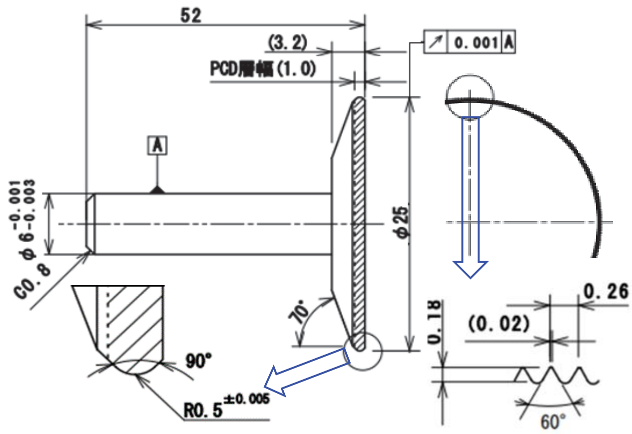
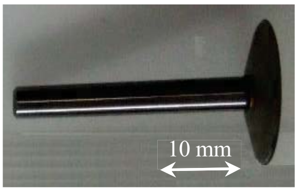


Fig. 2 Diagram of the developed milling tool made of PCD

substrate and the bonded PCD plate were cut to small cylindrical plates by wire EDM. The PCD plate was bonded on to a cemented carbide shank with a silver alloy. Finally, the end face and side face of the PCD chip was ground and polished with a diamond wheel, and the cutting edges were ground by a sharp diamond wheel. Fig. 2 shows a diagram of the newly developed polycrystal diamond (PCD)



micro milling tool and Fig. 3 shows a photograph of the tool.

Table 1 Specification of the PC

D tool

Material	PCD
Diameter	Φ25 mm
Number of cutting edge	300
Depth	0.18 mm

Fig. 3 View and specification of the developed PCD milling tool

3. Experimental set-up and cutting method

The PCD tool was attached to a 4-axes (X, Y, Z, C) ultra-precision machine, ULG100D(H_3) (Toshiba machine) as shown in Fig. 4. Three types of CVD-SiC workpieces with grain sizes of 10, 20, and 40 μm were vacuum-adsorbed on the worktable. Fundamental cutting experiments were performed by driving the tool in the X-axis direction while rotating it at a rotational speed of 10,000 min^{-1}. The cutting forces in the X-, Y-, and Z-axis directions were measured by a power meter (Kistler).

Ultra-precision machining of aspheric lens shapes on CVD-SiC was performed using PCD tools. In the fundamental experiments, CVD-SiC (Tokai Engineering) was used as a workpiece. The workpiece spindle was rotated at a speed of 100 min-1 and the tool was driven in the X-axis direction at a speed of 10,000 min-1 to machine the aspheric lens. The aspheric lens was machined by making 20 cuts with a depth of cut of 0.5 μm in a flat polished CVD-SiC.

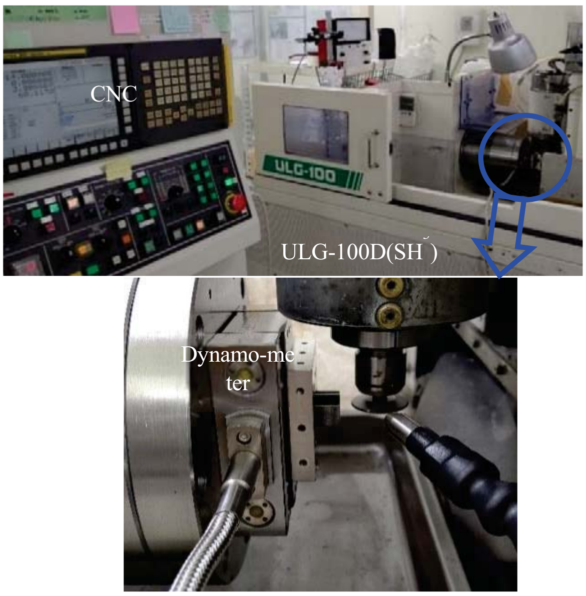


Fig. 4 View of cutting experiment by ultraprecision cutting machine

4. Experimental results of fundamental cutting tests

Three types of CVD-SiC with different grain sizes were milled by the developed the PCD tool to generate U-grooves. Cutting conditions are shown in Table 2. Fig. 5 shows the processing resistance of CVD-SiC with a grain size of 10 μm. The normal force was 1.81 N for the PCD tool when the depth of cut was 25 μm. In order to evaluate the cutting efficiency of the tool, the machining force ratio, λ is defined by the next equation:

$$\lambda = \frac{Fn}{Ft} \quad (1)$$

Where *Fn* is normal force, and *Ft* is tangential force. Fig. 6 shows the machining force ratios of three types of CVD-SiC with grain sizes of 10, 20, and 40 μm. The machining force ratio was almost constant at about 0.15 to 0.25.

To calculate the cutting efficiency of the tool, the specific machining energy, *e* was defined by the next equation:

$$e = \frac{Ft \cdot V}{b \cdot t \cdot v} \quad (2)$$

Where *V* is the tool speed, *b* is the tool width, *t* is the depth of cut, and v is the feed rate. The specific machining energy of each tool is shown in Fig. 5. The specific machining energy is higher when the depth of cut is smaller, and this was because of the effect of tool edge roundness.

Table 2 Cutting conditions for fundamental cutting test

	Cutting	Grinding
Workpiece	CVD-SiC	
Grain size	26.9 μm	
Diameter	Φ9.7 mm	
Rotation	10,000 min^{-1}	
Tool	PCD milling tool	Diamond wheels
Grain size		#1500
Diameter	Φ25 mm	Φ27 mm
Rotation	10,000 min^{-1}	10,000 min^{-1}
Depth of cut	0.5 μm	
Feed rate	0.1 mm/min	
Coolant	Water base coolant	White kerosene mist

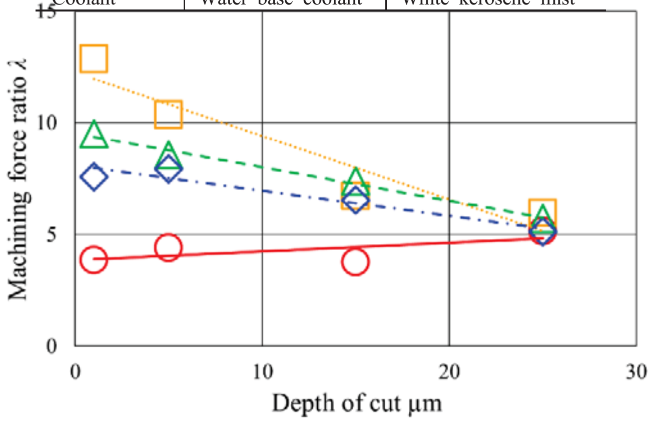


Fig. 5 Cutting forces of PCD tool compared with each wheel

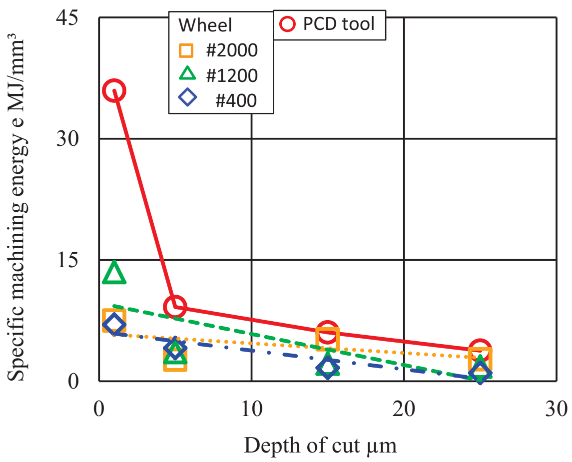
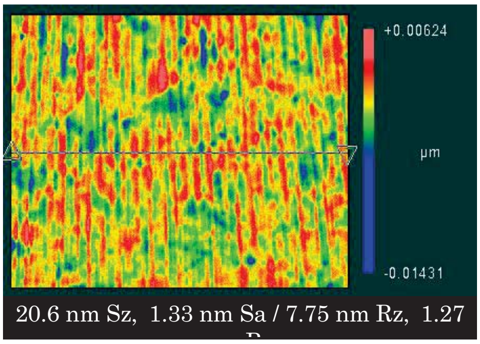
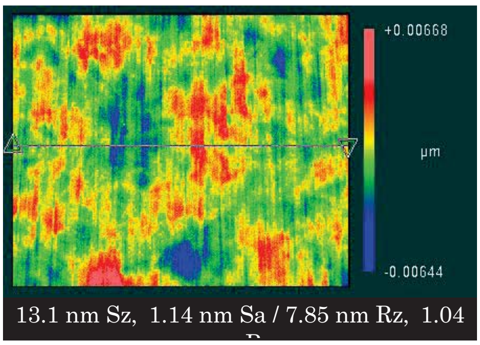


Fig. 6 Specific machining energy compared with each tool

Fig. 7 shows measured surface roughness profiles of the machined CVD-SiC mold. Micro scratches were generated by the cutting edges of the PCD milling tool without a micro crack, which indicates that the cut surface was ductile mode. The PCD milling tool was harder than that of the diamond grinding wheels, and the tool parameters such as a rake angle, a relief angle, a pitch, and a flute hight were controlled based on the tool design. The cutting characteristics were then stable, and the surface roughness was lower.



(a) Cutting by PCD



(b) Grinding by diamond wheel

Fig. 7 Surface roughness profiles of machined mold of CVD-SiC (f=0.1mm/min, Radial position: 0.5 mm)

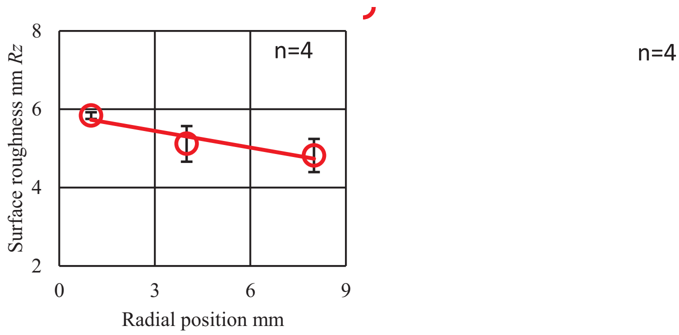
5. Aspherical cutting test

Aspherical molds of CVD-SiC were cut using the developed milling tool. Cutting conditions are shown in Table 3. As a workpiece, CVD-SiC of 26.9 µm in grain size was used and its approximate radius curvature was 15 mm. Depth of cut was 0.5 µm, cutting times was 20, and feed rate was 0.1 mm/min.

The surface roughness of the machined aspherical mold cut using the developed milling tool was measured at radial position of 1, 4, and 8 mm with a white interferometer. Fig. 8 shows the change of surface roughness for each radial position. Surface roughness of 4 - 6 nm Rz and 0.65 - 0.8 nm Ra were obtained using the developed PCD tool.

Table 3 Cutting conditions for the aspheric cutting

Workpiece Grain size Approximate radius curvature Rotation	CVD-SiC 26.9 µm 15 mm R 100 min^{-1}
Tool Diameter Rotation	PCD milling tool Φ25 mm 10,000 min^{-1}
Depth of cut Cutting times Feed rate	0.5 µm 20 0.1 mm/min
Coolant	Water base coolant



(a) Absolute values (Rz) (b) Arithmetic average (Ra)

Fig. 8 Change of surface roughness in aspherical molds cutting by the developed PCD milling tool

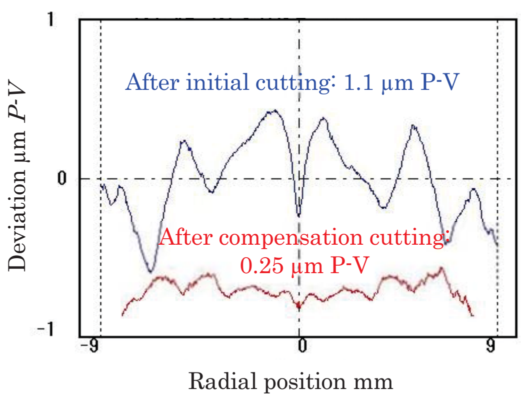


Fig. 9 Aspherical form accuracy

Fig. 9 shows the form accuracy of aspherical mold. The form profiles were measured by a non-contact laser probe scanner with a blue laser of short wavelength and calculated using the aspheric analysis program and a personal computer. A form accuracy after a primary cutting was 1.1 μm P-V because of the tool edge radius error and the tool position error. By analyzing these factors, the compensation machining was done and then, the form accuracy was improved to 0.25 μm P-V.

6. Conclusions

A milling tool made of polycrystalline diamond (PCD) were developed by wire EDM and grinding to machine aspheric ceramic molds more precisely and more efficiently. Fundamental cutting experiments show that the cutting force of the newly developed PCD tool was equivalent to that of a #1200 diamond wheel. Surface roughness of the surface machined by the developed PCD tool was better than that of a conventional diamond wheel in the flat cutting experiment. In the aspherical cutting test, the molds of CVD-SiC were cut in the ductile mode with the PCD milling tool. Surface roughness of 4 - 6 nm Rz and 0.65 – 0.8 nm Ra were obtained. The form accuracy of the aspheric mold obtained was 0.25 μm P-V.

REFERENCES

1. Brinksmeier E, Mutlugünes Y, Klocke F, Aurich J. C, Shore P and Ohmori H, Ultra-precision grinding CIRP Annals – Manufacturing Technology, Vol.59, No.2, pp. 652–671, 2010.
2. Suzuki H, Muramatsu A, Ymamoto Y, Okino T and Moriwaki T, Precision molding of micro aspherical glass lenses Proceedings of 5th euspen International Conference Montpellier, Vol. 1, No. 2, pp. 41-44, 2005.
3. Suzuki H, Okada M, Yamagata Y, Morita and S, Higuchi T, Precision grinding of structured ceramic molds by diamond wheel trued with alloy metal, CIRP Annals – Manufacturing Technology, Vol. 61, No. 1, pp.283–286, 2012.
4. Suzuki H, Hamada S, Okino T, Kondo M, Yamagata Y and Higuchi T, Ultraprecision finishing of micro-aspheric surface by ultrasonic two-axis vibration assisted polishing, Annals of the CIRP, Vol. 59, No. 1, pp.347-350, 2010.
5. Beauchamp A, Namba Y, Combrinck H, Phillip C and Freeman C, Shape adaptive grinding of CVD silicon carbide, CIRP Annals – Manufacturing Technology, Vol. 63, No. 1, pp. 317-320, 2014.
6. Shamoto E and Moriwaki T, Ultraprecision diamond cutting of hardened steel by applying elliptical vibration cutting, Annals of the CIRP, Vol. 48, No 1, pp. 441-444, 1999.
7. Suzuki H, Moriwaki, T, Yamamoto Y, and Goto Y, Precision cutting of aspherical ceramic molds with micro PCD milling tool, Annals of the CIRP, Vol. 56, No. 1, pp. 131-134, 2008.
8. Butler-Smith P, Axinte D and Daine M, Solid diamond micro-grinding tools from innovative design and fabrication to preliminary performance evaluation in Ti-6Al-4V, International Journal of Machine Tools and Manufacture, Vol. 59, pp. 55-64, 2012.
9. Butler-Smith P, Axinte D, Pacella M and Fay W, Micro/nanometric investigations of the effects of laser ablation in the generation of micro-tools from solid CVD diamond structures, Journal of Materials Processing Technology, Vol. 213, No. 2, pp. 194-200, 2012.
10. Suzuki H, Okada M, Asai W, Sumiya H, Harano K, Yamagata Y and Miura K, Micro milling tool made of nano-polycrystalline diamond for precision cutting of SiC, CIRP Annals – Manufacturing Technology, Vol. 66, No. 1, pp. 93–96, 2017.