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Precision cutting of CVD-SiC aspheric mold by PCD milling tool

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Abstract
Demands are increasing for micro-optics for various optical devices, such as digital cameras, smart phone, and automobile sensors. Most of the components are made of plastics, and however, glass lenses are also required for optical systems of high added value. The aspheric glass lenses are press-molded by ceramic dies and molds of tungsten carbide (WC) and silicon carbide (SiC). The dies and molds are mostly ground using 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. Furthermore, the size of the dies and molds are becoming smaller, and the required accuracy is becoming higher. It is, therefore expected that the ceramic dies and molds could be finished precisely by development of a proper diamond cutting tool. In this study, engineering tool, or micro milling tools of polycrystalline diamond (PCD) are proposed and developed by micro electric discharge (EDM) for high efficiency and high precision machining tool of ceramics. In this cutting method, the materials are removed by an interrupted cutting and the tool wear can be decreased. It is therefore expected that much harder SiC can be cut with micro structured milling tool. In the fundamental cutting experiments, CVD-SiC molds were tested to cut, and the cutting performances of cutting force and surface roughness were evaluated. In the aspherical cutting test, the aspherical mold of CVD-SiC was cut and the highly efficient and high accurate cutting performance are shown.

Keywords: polycrystalline diamond tool, CVD-SiC, precision cutting, milling, wire EDM.

1. Introduction

Micro aspheric glass lenses have been used in various devices, such as digital camera, smart and mobile phone with micro camera, DVD / CD pick-up system, optical transmission devices, and virtual reality devices. The aspheric glass lenses are generally mass produced at a high temperature of 400–800 °C by glass press-molding process using ceramic molds made of tungsten carbide (WC) or silicon carbide (SiC) [1][2]. In recent years, demands of CVD-SiC have been increasing for longer life and higher precision of molds, which have higher hardness, higher wear resistance, higher thermal shock resistance, and a super fine surface. The ceramic molds were conventionally ground using micro diamond wheels. The diamond wheel must be trued carefully on the machine before grinding, however the grinding wheel wore soon, and it was difficult to keep the original geometrical shape of the wheel [3][4][5]. In this study, a milling tool made of polycrystalline diamond (PCD) was developed to machine aspheric ceramic molds more precisely and more efficiently [6]. In the cutting experiments, a flat shape of CVD-SiC was cut with the developed milling tool installed to high precision/high speed air bearing spindle to evaluate the machining efficiency and the surface roughness. Finally, aspheric cutting experiments of CVD-SiC were carried out using the developed PCD milling tool.

2. Development of PCD milling tool

The PCD milling tool was fabricated using EDM process, as shown in Figure 1. The PCD is conductive material and can be machined using EDM process, as shown in Fig.1. The PCD wafer was bonded with a silver alloy onto a cemented carbide substrate and the bonded PCD plate was cut into small cylindrical plates by wire EDM. The PCD plate was bonded on to a cemented carbide shank with a silver alloy [7]. The end face and side face of the PCD chip was ground with a diamond wheel, and the cutting edges were ground by a sharp diamond wheel [8][9][10]. The PCD micro milling tool is shown in Figure 2. Table 1 shows the tool specifications.

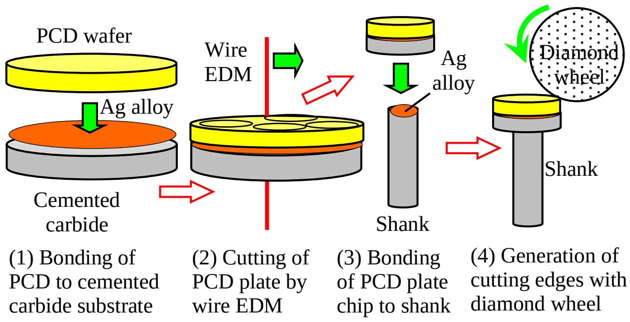


Figure 1. Machining process of the PCD milling tool

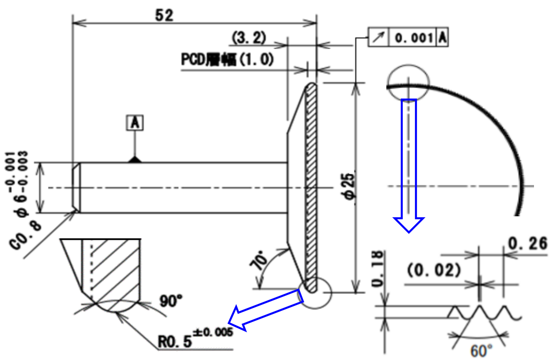


Figure 2. The developed PCD milling tool

Table 1 Specifications of the developed PCD milling tool

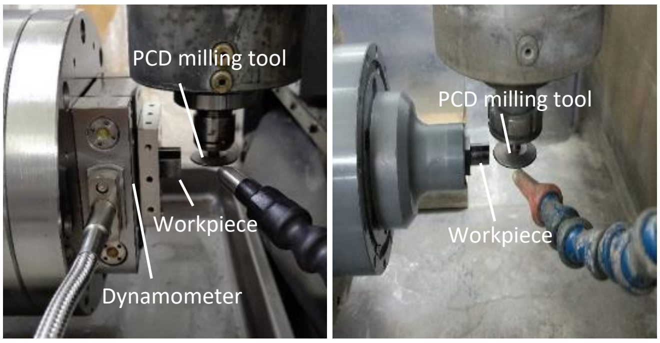
Material	PCD (Polycrystalline diamond)
Diameter	Φ25 mm
Number of cutting edge	300
Rake angle	-30 degrees
Relief angle	60 degrees
Depth	0.18 mm

3. Experimental set-up and method

In the fundamental cutting experiments, CVD-SiC workpieces were machined using the conventional diamond wheels and the developed PCD tool for comparing their characteristics. The tool was attached to a 4-axes (X, Y, Z, C) ultra-precision machine, ULG100D(SH_3) (Toshiba machine) as shown in Figure 3. The CVD-SiC workpieces were vacuum-chucked onto the workpiece table. The fundamental cutting test was performed by driving the tool in the X-axis direction, while rotating it at a rotational speed of 10,000 min^{-1}. Cutting forces in the X-, Y-, and Z-axis directions were measured by a dynamometer (Kistler).

Flat cutting of CVD-SiC was carried out using the tools. The work spindle was rotated at 100 min^{-1} and the tool was driven at 10,000 min^{-1} in the X-axis direction to perform the machining. The surface roughness was measured by a white light interferometer.

In the aspheric cutting test, the PCD tool was attached to perform ultra-precision machining of aspheric lens shapes. The machining was performed with simultaneous two-axis control of X and Z axes. The aspheric lens was machined by making 20 cuts with a depth of cut of 0.5 µm in a flat polished CVD-SiC.



(a) Fundamental cutting tests (b) Flat cutting tests

Figure 3. Views of ultraprecision cutting

4. Experimental results

4.1. Fundamental cutting tests

Cutting conditions are shown in Table 2. Figure 4 shows the cutting forces of CVD-SiC by each diamond tool. Cutting forces by the developed PCD tool were similar to that by #1200 wheel in gran size.

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

$$e = (F_t \cdot V) / (b \cdot t \cdot v) \quad (1)$$

F_t is the cutting force, 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 Figure 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 of fundamental cutting tests

	Cutting	Grinding
Workpiece Grain size	CVD-SiC 26.9 µm	
Tool Grain size Diameter Rotation	PCD milling tool Φ25 mm 10,000 min^{-1}	Diamond wheels #2000, #1200, #400 Φ50 mm 5,000 min^{-1}
Depth of cut	1, 5, 15, 25 µm	
Feed rate	10.0 mm/min (Down cut)	
Coolant	White kerosene mist	

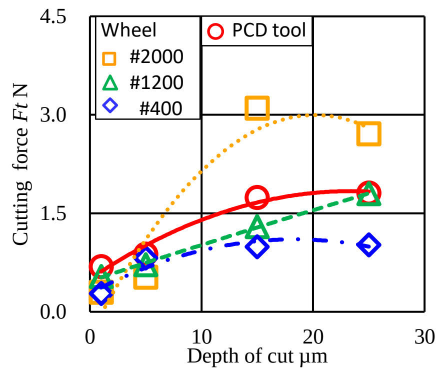


Figure 4. Cutting forces compared with each tool

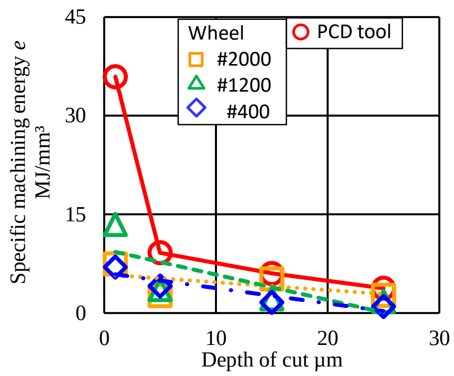
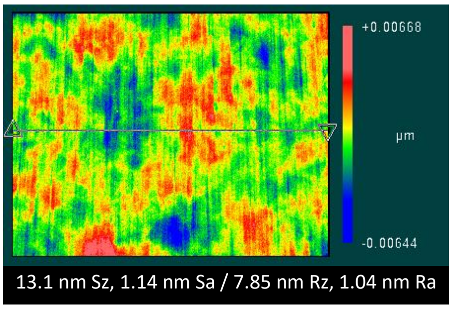


Figure 5. Specific machining energy compared with each tool

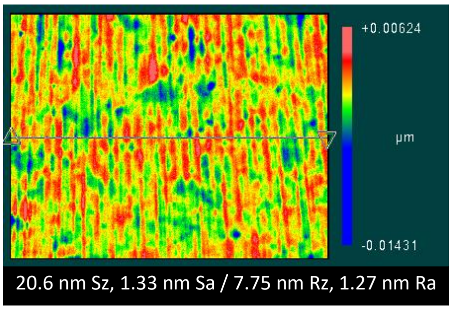
Cutting conditions are shown in Table 3. Figure 6 shows measured surface roughness profiles of the machined CVD-SiC mold. Micro scratches were generated by the cutting edges of the PCD milling tool without a micro crack, which indicates that the cut surface was ductile mode. The surface roughness profiles after grinding and after cutting are shown in Figure 7. 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.

Table 3. Cutting conditions of flat cutting

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



(a) Cutting using PCD



(b) Grinding using diamond wheel

Figure 6. Surface roughness profiles of machined mold of CVD-SiC (f=0.1mm/min, Radial position: 0.5 mm)

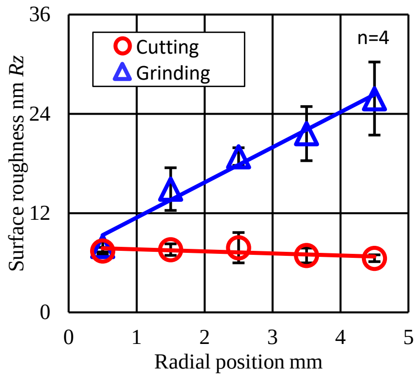


Figure 7. Change of surface roughness in flat machining

4.2. Aspherical cutting test

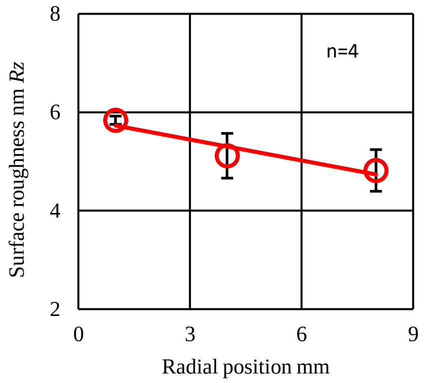
Aspherical molds of CVD-SiC were cut using the developed milling tool. Cutting conditions are shown in Table 4. As a workpiece, CVD-SiC of 26.9 µm in grain size was used and its approximate radius curvature was 15 mm. Depth of cut was 0.5 µm, cutting times was 20, and feed rate was 0.1 mm/min.

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. Figure 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.

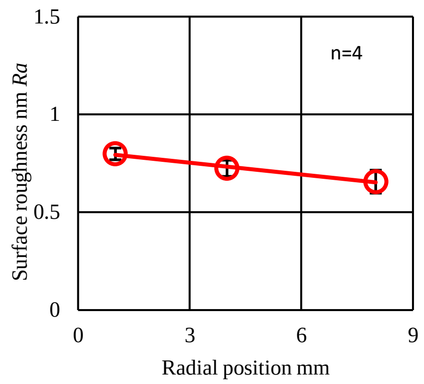
Figure 9 shows the form accuracy of aspherical mold. The form profiles were measured by a non-contact laser probe scanner with a blue laser of short wavelength and calculated using the aspheric analysis program and a personal computer. A form accuracy after a primary cutting was 1.1 µm *P-V* because 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*.

Table 4. Cutting conditions for the aspheric catting

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



(a) Absolute values (Rz)



(b) Arithmetic average (Ra)

Figure 8. Change of surface roughness in aspherical molds cutting using the developed PCD milling tool

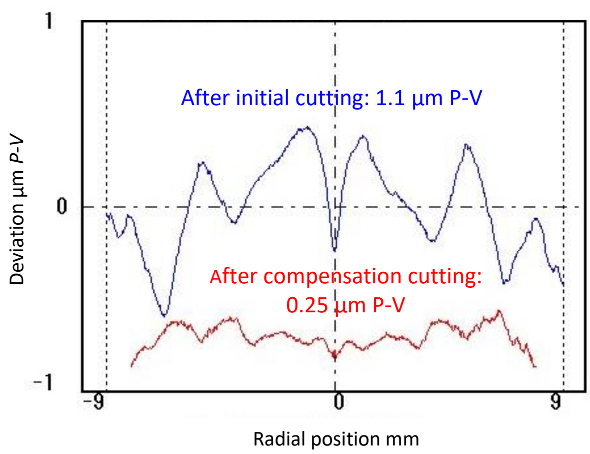


Figure 9. Aspherical form accuracy

5. 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*.

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