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Development of micro milling tool made of single crystalline diamond for ceramic cutting

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ABSTRACT

In order to machine micro aspheric ceramic molds precisely and efficiently, micro milling tools made of single crystalline diamond (SCD) are developed. Many cutting edges are fabricated 3-dimensionally on the edge of a cylindrical SCD by a laser beam. Flat binderless tungsten carbide mold was cut with the developed tool to evaluate the tool wear rate and its life. Some micro aspheric molds of tungsten carbide were cut with the tool at a rotational speed of 50,000 min^{-1}. The molds were cut in the ductile mode. The form accuracy obtained was about 100 nm *P–V* and the surface roughness 12 nm R_z.

1. Introduction

Micro aspheric glass lenses have been used in various devices, such as digital cameras, laser devices and medical devices. The micro glass lenses are generally mass produced in high temperature of 400–800 °C by glass press molding process with molds or ceramic molding dies made of tungsten carbide or silicon carbide. The aspheric ceramics molds are mostly ground with micro diamond wheels and polished with loose abrasives. The workpiece form accuracy of 0.1–0.2 μm *P–V* and the surface roughness of 10–30 nm R_z are obtained by the grinding [1–3]. However, the grinding wheel wears soon and it is difficult to keep the original geometrical shape and surface of the wheel, and then, the diamond wheel must be trued carefully on the machine after some grinding. 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 molds becomes smaller and the required accuracy becomes higher [1]. The ultrasonic elliptical vibration cutting method is developed by Shamoto and is applied to mirror machining of harden steels with single crystalline diamond tool [4]. The micro milling tools made of polycrystalline diamond (PCD) are developed and are applied to ultraprecision machining of tungsten carbide molds [5]. Butler-Smith developed micro structured tools made of CVD diamond with a pulse laser and a focus ion beam, and fundamental grinding tests of hard materials such as Ti-Al-4V are carried out and the tool performance are evaluated [6,7]. In these cutting methods, the tool wear is decreased by the interrupted cutting effects and the hard materials can be removed precisely.

In order to machine micro aspheric ceramic molds more precisely and more efficiently, in this study, micro milling tools made of single crystalline diamond (SCD) are developed. Many cutting edges of the milling tool are fabricated 3-dimensionally by a laser beam, respectively, at the edge of a small cylindrical SCD tool, which is bonded to the tungsten carbide shank. In the cutting experiments, flat shape of binderless tungsten carbide was cut with the developed milling tool installed to high precision/high speed air bearing spindle to evaluate the tool wear process and wear rate. Finally, twenty micro aspheric molds of binderless tungsten carbide were cut in the ductile mode with the developed tool. The form accuracy obtained was about 100 nm *P–V* and the surface roughness 12 nm R_z.

2. Development of SCD micro milling tool

Fig. 1 shows a micro fabrication process of the newly developed micro milling tool made of a single crystalline diamond (SCD). At first the SCD chip machined to cylindrical shape by laser beam was bonded with a silver alloy on to a cemented carbide shank. Finally, the end face of the SCD chip was machined 3-dimensionally with a laser beam, and the cutting edges of structured surface were fabricated. Fig. 2 shows a view of laser machining of 3D scanning. The IR YVO_4 laser (λ = 1.064 μm) was used. The laser head was installed to 3-axes controlled machine.

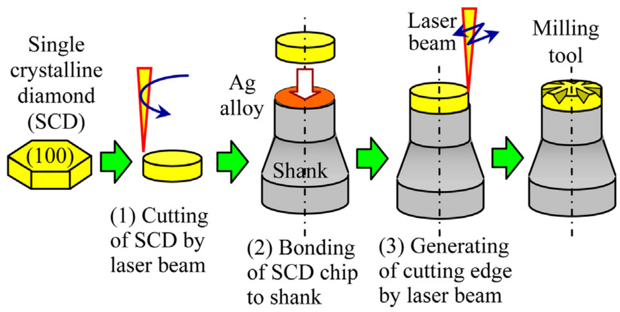

Fig. 1. Micro fabrication process of the SCD milling tool.

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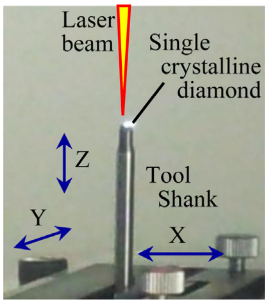

Fig. 2. View of laser fabrication of 3D scanning.

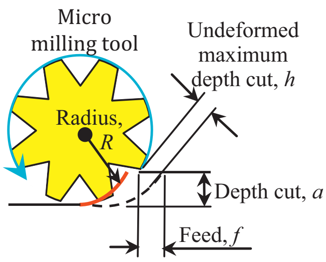

Fig. 3. Illustration of interrupted cutting in micro milling.

The undeformed maximum depth cut, h, in the milling by the tool edges is given by the next equation, as shown in Fig. 3.

$$h = \frac{f}{n}\sqrt{\frac{2a}{R}} \qquad (1)$$

where f is a feed rate, n is a number of the cutting edges of milling tool, and a is an apparent depth cut and R is a tool radius.

This equation shows real undeformed depth cut is much smaller than the apparent depth cut and therefore precision surface will be obtained. Secondly tool is rotating and the workpiece form accuracy is independent on tool roundness. Thirdly the interrupted cutting makes the tool temperature and tool wear reduced and then it is expected that hard and brittle materials could be cut ultraprecisely and efficiently.

Fig. 4 shows SEM images of the developed micro SCD milling tools fabricated by the laser fabrication as shown in Fig. 1. Fig. 4(a) is a tool with sharp edges and Fig. 4(b) is a tool with round edges of 1 mm. In the cutting experiments, the tool with sharp edges of Fig. 4(a) was used to evaluate the cutting performances.

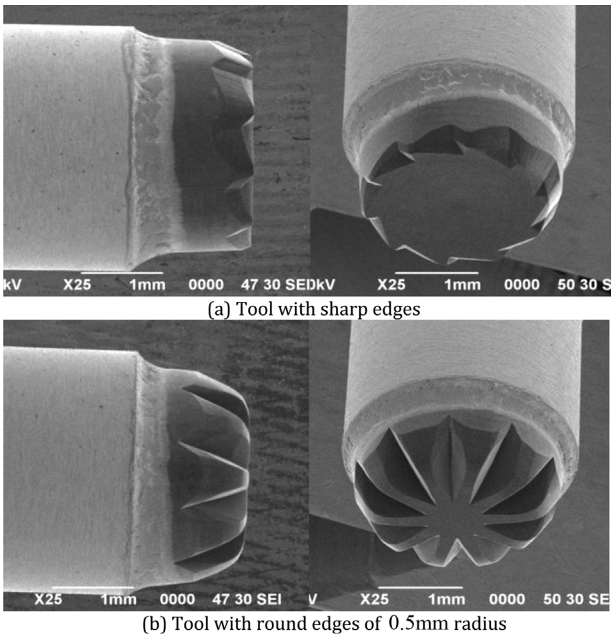

Fig. 4. SEM images of micro SCD milling tools fabricated by laser beam.

Table 1
Specifications of milling tools.

Material	Single crystalline diamond
Outer diameter	Φ 2 mm
Edge radius	0 and 0.5 mm
Rake angle	-40°
Relief angle	0°
Number of cutting edges	10

Specifications of the milling tools used in the cutting experiment are shown in Table 1.

3. Experimental set-up and method

The SCD micro tool was attached to a 4-axes (X, Y, Z, and C) controlled ultra-precision machine, Toshiba ULG100D(H3) as shown in Fig. 5. The tool spindle is an air-bearing spindle with the maxim rotational speed of 60,000 min^{-1}. The tool was actuated in X, Y and Z-axes by the linear scale feedback system with 1 nm positioning resolution. In the cutting test, the workpiece was vacuum chucked onto the workpiece air spindle (C-axis table). The SCD micro milling tool was chucked with a collet chuck to the air spindle on the Y-axis table.

In the preliminary cutting experiments, the workpiece of binderless tungsten carbide was machined and the tool wear was evaluated by measuring the replica of the tool transcribed on to the carbon plate as shown in Fig. 6. The tool wear in the machining by the milling tool and tool life were evaluated. In the measurements of replica, a non-contact laser probe scanner with a blue laser of short wavelength (λ = 0.473 μm) was used [8].

In the aspheric cutting experiments, the cylindrical workpiece of binderless tungsten carbide was used. The aspheric workpiece was cut with simultaneous 2-axes (X and Z) control.

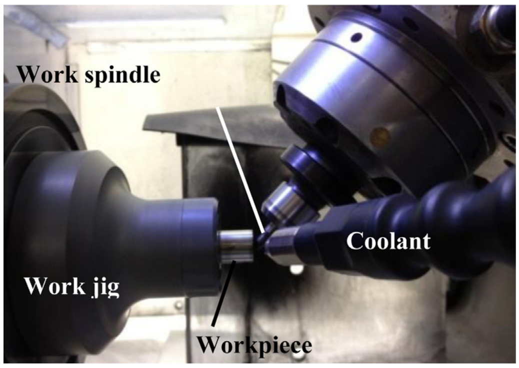

Fig. 5. View of preliminary and aspheric cutting experiments.

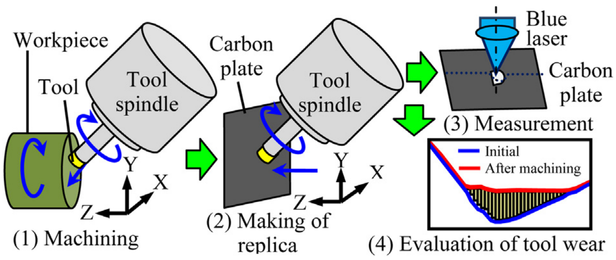

Fig. 6. Evaluation method of tool wears.

4. Preliminary cutting experiments

In the preliminary cutting tests, the tool wear rate and its life in the milling with the milling tool or interrupted cutting are evaluated. In the experiments, flat shape of tungsten carbide was cut with the developed SCD milling tool.

At first, in order to evaluate the tool wear characteristics of the developed SCD milling tool, the flat shape of tungsten carbide was cut at the condition of Table 2. The feed rate was 0.5 μm/rev. and