IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 17, Issue 5 Ser. V (Sep. – Oct. 2020), PP 01-06
www.iosrjournals.org

Precision Cutting of the Ceramic Mold by the Micro-Milling Tool

Nguyen Minh Quang[1], Pham Van Trinh[1]
[1]*Faculty of Mechanical Engineering, Hanoi University of Industry, Tu Liem District, Ha Noi, Vietnam*

Abstract: *In order to machine harder ceramics precisely, micro milling tools made of binderless nano-polycrystalline diamond (NPD) were fabricated by using laser fabrication process. Several cutting edges were fabricated three-dimensionally by a laser beam on the edge of a cylindrical NPD. SiC wafers with a flat face were cut with the developed tool to evaluate the tool wear rate and its life. From the fundamental experiment of tool wear, the tool wear in NPD tool is extremely small compared to that in conventional single crystalline diamond (SCD) tool. Finally, some micro textured molds of SiC (single crystal SiC, CVD-SiC) were cut with the tools at a rotational speed of 50,000 min*$^{-1}$*. The molds were cut in the ductile mode. The form accuracy obtained using NPD was extremely high compared to that obtained using conventional SCD.*

Keywords: *ultraprecision cutting, milling tool, ceramics, nano polycrystalline diamond, ductile mode cutting*

Date of Submission: 15-10-2020 Date of Acceptance: 31-10-2020

I. Introduction

Micro aspheric glass lenses for digital cameras and mobile phones are manufactured by glass press molding process with precise ceramic molds made of silicon carbide (SiC) or tungsten carbide (WC). The aspheric ceramic molds are ground with a diamond wheel and polished with loose diamond abrasives [1, 2]. However in the conventional grinding process, the wears of the diamond wheel is large and the wheel life is not long and the grinding accuracy is not so high. In this study, in order to overcome these problems cutting with milling tools of diamond tool are proposed and feasibility of machining are studied. The micro milling tool of diamond is fabricated by a laser scanning process [3-5]. In the former report, some micro aspheric molds of tungsten carbide were cut with the tool [4]. The molds were cut in the ductile mode and the feasibility of ultraprecision machining was clarified. In this paper, in order to machine harder ceramics precisely, micro milling tools made of nano- polycrystalline diamond (NPD) were fabricated [6-8]. Many cutting edges were fabricated three- dimensionally on the edge of a cylindrical NPD by a laser beam. Flat shape of ceramic wafer was cut with the developed tool to evaluate the tool wear rate and its life. Some micro aspheric molds of ceramics such as silicon carbide were cut with the tool at a rotational speed of 50,000 $^{-1}$. The molds were cut in the ductile mode.

II. Experimental procedures

1. Development of micro milling tool of nano-polycrystalline diamond (NPD)

Fig. 1 shows the fabrication process for a micro milling tool from nano crystalline diamond (NPD). First, the NPD chip was bonded with a silver alloy onto a cemented carbide shank. The outer surface of the NPD chip is machined using a laser beam to decrease the runout of the tool in less than 1μm. Finally, the end face of the SCD chip is fabricated three-dimensionally through a laser beam, and the cutting edges of the structured surface were fabricated. A Q switched IR YVO4 laser (λ=1.064 μm) was used to scan three-dimensionally by a Galvanometer mirror [3-5].

Fig. 2 shows scanning electron microscopy images of the developed micro milling tools of the NPD that was fabricated using the laser fabrication process. Specifications of the NPD tool used in the cutting experiments are shown in Table 1.

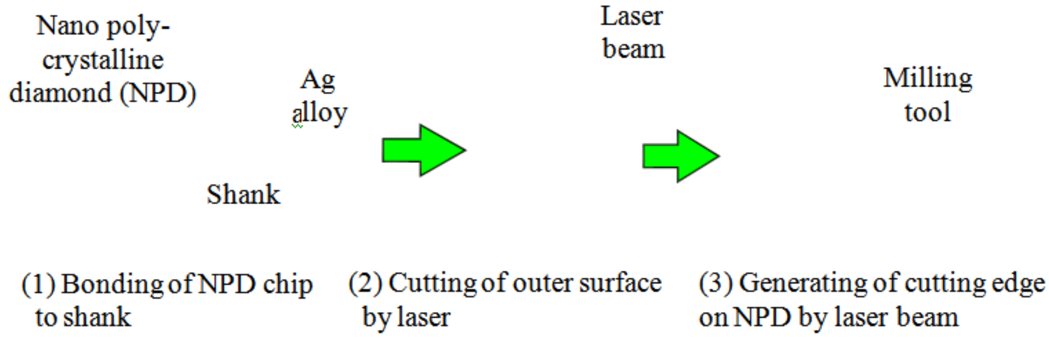


Fig. 1 Laser fabrication process of the micro milling tool made of a nano-polystalline diamond (NPD)

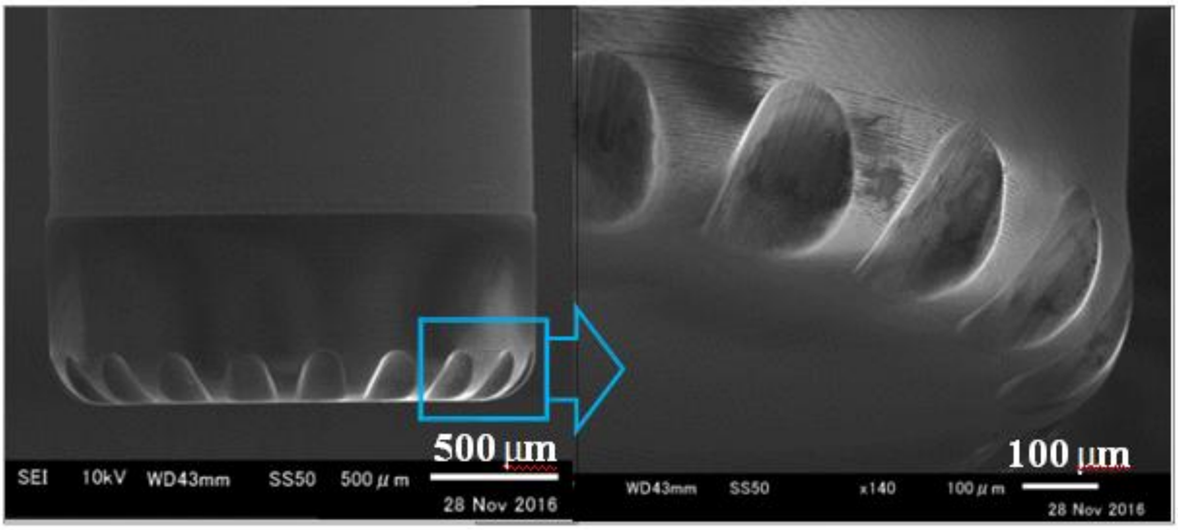


Fig. 2 SEM images of laser fabricated micro NPD milling tools (Edges radius: 0.2 mm)

Table 2. Specifications of NPD milling tool

Material	Nano poly-crystalline diamond
Outer diameter	Φ 2 mm
Rake angle	-40°
Relief angle	0°
Width of cutting flutes	0.075 mm
Edge radius	0.2 mm
Number of cutting edges	20

III. Experimental method of took wear

Fig. 3 shows the cutting experimental set-up. The NPD tool was chucked with a shrinkage fitting chuck system to the 45° tilted air spindle. The NPD micro milling tools were attached to a 3-axis (X, Y, Z) controlled ultraprecision machine, ULG100A(HY). The machine was actuated by a ball screw driven system with a positioning resolution of 10 nm.

In the preliminary cutting experiments, a micro lens array mold with many concave spheres was machined using the developed NPD milling tool as shown in Fig. 4(a). The micro lens array molds of SiC (CVD-SiC or single crystalline SiC) were machined using the round shaped tool depicted in Fig. 2. A graphite carbon plate was also attached to the workpiece jig, and the plate was machined by in-feed cutting of the tool. A replica of the tool was made after the nine spherical molds were cut. This motion was repeated eight times to machine a total of 72 spherical molds. The method of machining one spherical mold is shown in Fig. 4(b). The edge of the milling tool was scanned along the spherical traces for a total of 20 times. After the cutting, the tool

wear was evaluated by measuring the replica of the tool transcribed on to the graphite carbon. The replicas were measured with a non- contact laser probe scanner with a blue laser of short wavelength (λ=0.473 μm) [1].
Finally, application molds made of single crystalline SiC were machined for the trial. A micro spherical array mold was cut with simultaneous 2-axis (X, Z) control.

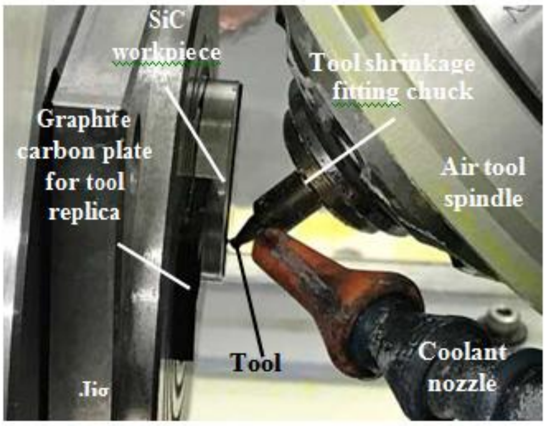


Fig. 3 View of cutting experiments

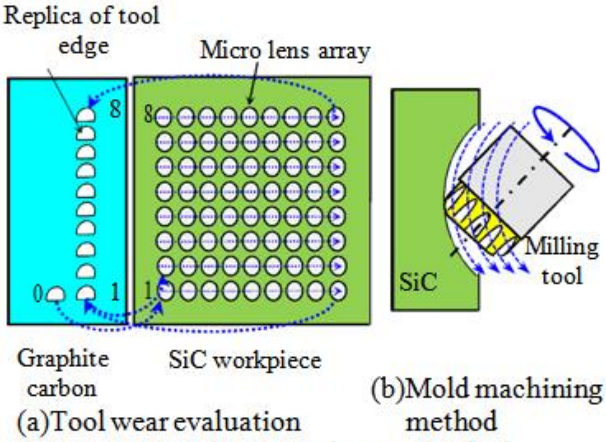


Fig. 4 Tool wear evaluation method

Table 3 Cutting conditions of tool wears evaluation.

IV. Results And Discussions

1. Results of took wear experiment

The tool wear was evaluated during the fundamental cutting tests. In the experiments, the flat shape of the SiC substrates (CVD-SiC and single crystalline SiC) were cut to generate micro lens arrays using both the conventional SCD milling tool and the developed NPD milling tool for comparison.

To evaluate and compare the tool wear characteristics of the conventional SCD and developed NPD milling tools, the flat shapes of SiC substrates were cut under the conditions listed in Table 3. In order to evaluate the tool wear rate, the tool wear ratio (Volume of machined workpiece / Volume of worn tool) was calculated [4].

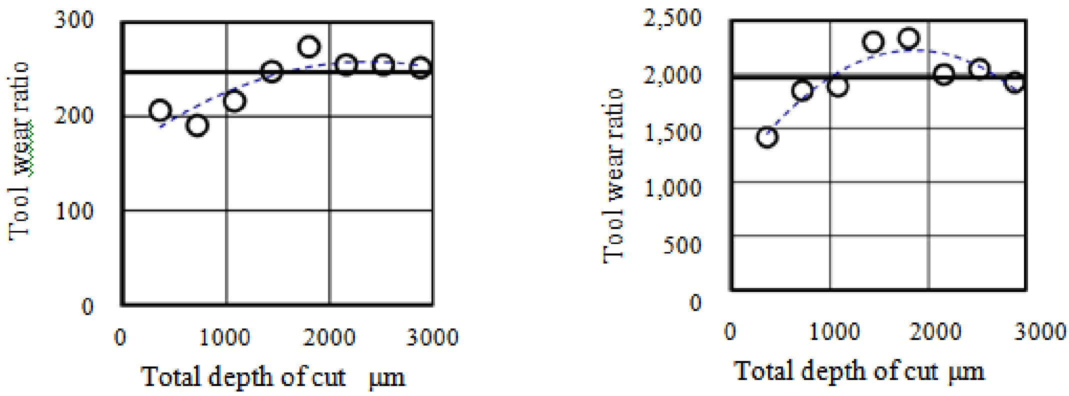
The tool wear ratio calculated is shown in Fig. 5. The workpiece was CVD-SiC. Fig. 5(a) shows the tool wear ratio cut with conventional single crystal diamond (SCD) and Fig. 5(b) shows the tool wear ratio cut with nano poly-crystalline diamond (NPD). The tool wear ratio of the NPD was very small at approximately 1/8 as compared with that of the SCD.

Similarly, the flat shape of a single crystalline SiC wafer was cut under the conditions listed in Table 3 to evaluate and compare the tool wear characteristics of the conventional SCD milling tool and the developed NPD milling tool. Fig. 6 shows the changes in the tool wear ratio calculated from identical experiments. Fig. 6(a) shows the result obtained using the conventional single crystalline diamond (SCD) tool, and Fig. 6(b) shows the results obtained using the developed NPD milling tool. These results demonstrate that the developed NPD milling tool was very effective for cutting CVD- SiC and single crystalline SiC.

The roundness of the worn cutting edges was measured on the circumference of the tool using a non-contact blue laser scanner after machining of the SiC substrates. Fig. 7(a) shows the roundness profile of the SCD milling tool after use. The crystal orientation of the tool top was the (100) face. Fig. 7(b) shows the roundness profile of the NPD milling tool after use. The characteristics of the tool wear rate appeared to be dependent on the crystal orientation [6-8]. From these results, it was found that the effective number of cutting edges in the NPD tool was large, which indicates that the NPD tool was effective at creating a ductile mode surface in hard materials. The cutting edges of the SCD tool did not wear equally because the hardness of the structure of the {100} face in SCD was not constant [9].

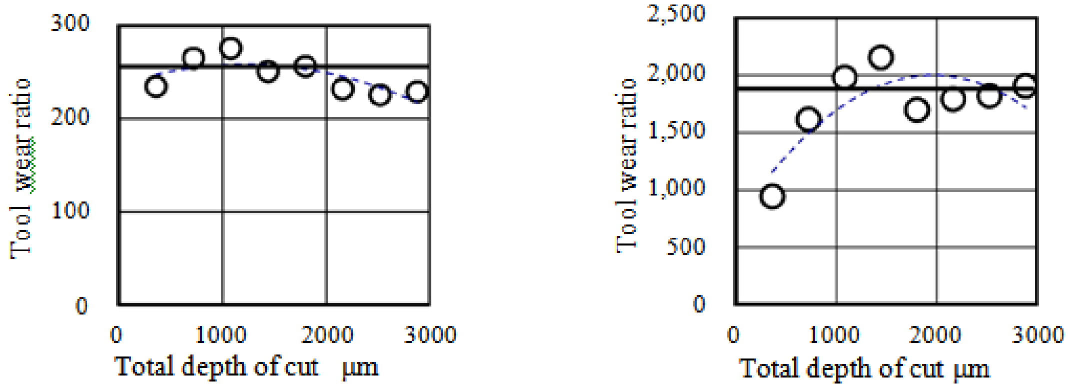
Table 3 Cutting conditions of tool wears evaluation

Tool material Rotation	Nano poly-crystalline diamond (NPD), Single crystalline diamond (SCD) 50,000 min^{-1}	
Workpiece Hardness	CVD-SiC 3175 HV	Single crystalline SiC (Si-face) 3623 HV
Shape Radius curvature	Spherical array (n_x 9 × n_y 8) 1.4 mm	
Depth of cut Cutting times Feed rate	2 μm 20 0.4 mm/min (8 nm/rev.)	
Coolant	Water base coolant (Solution type)	



(a) Tool: SCD tool (b) Tool: NPD tool

Fig. 5. Tool wear characteristics in milling of CVD-SiC



(a) Tool: SCD tool (b) Tool: NPD tool

Fig. 6. Tool wear characteristics in milling of single crystalline SiC

2. Generation of the micro textured surface

A micro array mold of single crystalline SiC with an ellipsoidal shape was machined with the SCD and developed NPD milling tools. The cutting conditions are shown in Table 4. The round shape of the milling tool (shown in Fig. 2) was used. A Nomarski micrograph of the machined mold is shown in Fig. 8. A very smooth and precise structured surface was created.

Fig. 9 shows the changes in surface roughness of the machined ellipsoidal array mold measured by a non-contact type measuring instrument. Fig. 9(a) shows the result obtained using the SCD tool and Fig. 9(b) shows the result obtained using the NPD tool. The surface roughness when the NPD tool was used, was found to be smoother. Fig. 10 shows the change in form deviations of the machined ellipsoidal array mold. Fig. 10(a) shows the result obtained using the SCD tool and Fig. 10(b) shows the result obtained using the NPD tool. The form accuracy created using the NPD tool was better. This was because the tool wear of the SCD tool was not equal, and the number of effective active cutting edges on the SCD tool edge decreased.

Table 4 Cutting conditions for machining elliptical array

Tool material Rotation	Nano poly-crystalline diamond (NPD) 50,000 min^{-1}
Workpiece Shape Radius curvature	Single crystalline SiC Elliptical array (n_x 9 × n_y 8) Rx=1.3 mm, Ry=2.7 mm
Depth of cut Sag (total depth of cut) Feed rate	1 µm 10 0.2 mm/min (4 nm/rev.)
Coolant	Water base coolant (Solution type)

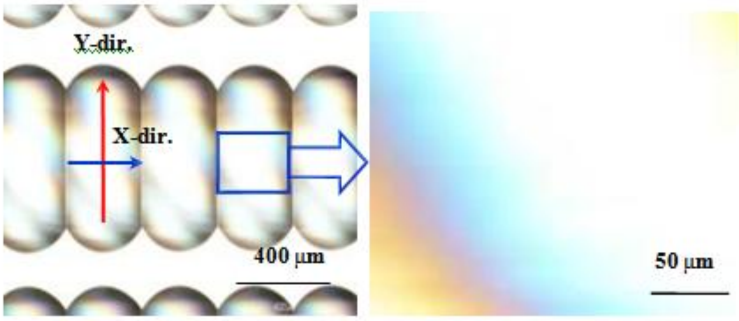
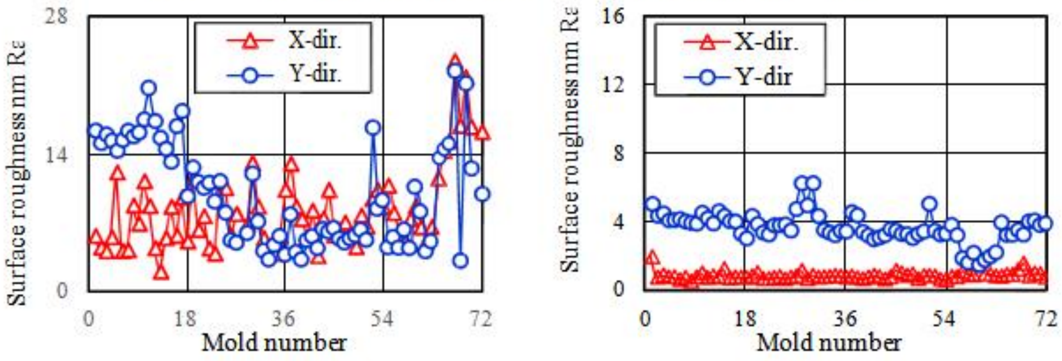
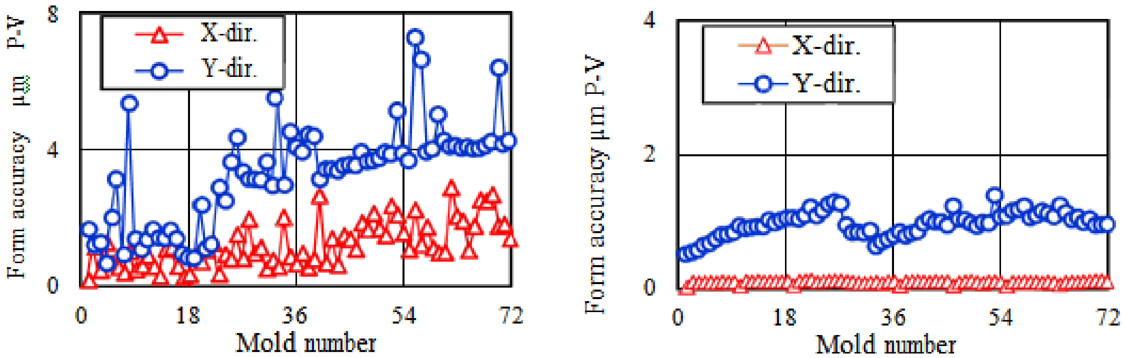


Fig. 8 Nomarski micrographs of machined ellipsoidal array mold



(a) Tool: SCD tool (b) Tool: NPD tool

Fig. 9 Changes in surface roughness of the machined ellipsoidal array mold.



(a) Tool: SCD tool (b) Tool: NPD tool

Fig. 10 Changes in form accuracy of the machined ellipsoidal array mold.

V. Summary

In order to machine a micro textured or structured surface on a SiC mold, micro milling tools made of binderless ultra-hard nano-polycrystalline diamond (NPD) were developed. NPD is harder than single crystalline diamond, and is also a much tougher and more homogeneous material. In cutting experiments on CVD-SiC and single crystalline SiC, the tool wear was evaluated while generation a micro textured surface on the SiC molds. The SiC molds were cut in ductile mode and very precise textures could be generated. From the cutting experiments, it was demonstrated that the developed NPD milling tool was capable of precisely and efficiently machining or texturing SiC ceramics.

References

[1]. Suzuki H, Okada M, Yamagata Y, Morita S, Higuchi T (2012) Precision Grinding of Structured Ceramic Molds by Diamond Wheel Trued with Alloy Metal. Annals of the CIRP 61(1): 283–286.
[2]. Funaki T, Nishio A, Kimoto T, Hikihara T (2008) A Study on Electro Thermal Response of SiC Power Module during High Temperature Operation. IEICE Electron. Express 5(16): 597-602.
[3]. Butler-Smith P, Axinte D, Pacella M, Fay W (2012) 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 213(2): 194–200.
[4]. Suzuki H, Okada M, Fujii K, Matsui S, Yamagata Y (2013) Development of Micro Milling Tool Made of Single Crystalline Diamond for Ceramic Cutting. Annals of the CIRP 62(1): 59–62.
[5]. Suzuki H, Moriwaki T, Yamamoto Y, Goto Y (2007) Precision Cutting of Aspherical Ceramic Molds with Micro PCD Milling Tool, Annals of the CIRP 56(1): 131-134.
[6]. Irifune T, Kurio A, Sakamoto S, Inoue T, Sumiya H (2003) Ultra-Hard Polycrystalline Diamond from Graphite. Nature 421: 599-600.
[7]. Sumiya H, Irifune T (2007) Hardness and Deformation Microstructures of Nano-Polycrystalline Diamonds Synthesized from Various Carbons under High Pressure and High Temperature. Journal of Material Research 22: 2345-2351.
[8]. Harano K, Satoh T, Sumiya H, Kukino S (2006) Cutting Performance of Nano-Polycrystalline Diamond, SEI Technical Review 71: 98-103.
[9]. Wilks, M E (1991) Properties and Application of Diamonds. Butterworth-Helnemaun Ltd: 310.

Nguyen Minh Quang, et. al. "Precision Cutting of the Ceramic Mold by the Micro-Milling Tool." *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, 17(5), 2020, pp. 01-06.