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# Tool wear control in diamond turning of high-strength mold materials by means of tool swinging

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ABSTRACT

A tool-swinging method was proposed to reduce tool wear in diamond turning of high-strength mold materials. A round-nosed diamond tool was swung by rotating the B-axis rotary table of the machine, the center of which was aligned with the tool center. The tool-decentering error was detected and compensated for by an on-machine measurement system. The effects of tool-swinging direction, swinging speed, lubricant type, and tool rake angle were investigated. The tool wear was greatly reduced compared to the conventional method. A surface finish of 4 nm Ra was obtained on reaction-bonded silicon carbide by generating continuous chips.



## 1. Introduction

High-strength ceramic materials, such as reaction-bonded silicon carbide (SiC) and tungsten carbide (WC), are widely used as molding dies for manufacturing ultraprecision aspherical glass lenses. Grinding, lapping, and polishing are usually used to fabricate optical surfaces using these high-strength materials [1–3]. Although these methods can produce an optical surface finish, the production cycle is long and the production cost is high. In particular, it is difficult for these methods to fabricate micro-structures and high-aspect ratio shapes [4]. For this reason, it is expected that ultraprecision cutting technology [5] could be used for machining high-strength molds. However, tool wear control is a challenge in the cutting of ceramic materials. Although ultrasonic vibration-assisted cutting is an effective method to reduce tool wear and has been successfully used for machining hardened alloys [6], there is no report on its successful application to ceramics machining. An alternative approach might be rotary cutting. Rotary tools have been shown to be effective for use in the cutting of hard metals [7]. However, conventionally, rotary tools are made of ceramics, such as tungsten carbide, and it is technologically difficult to fabricate a rotary tool using single crystalline diamond. In the present study, a tool-swinging cutting method is proposed to realize ultraprecision rotary cutting using single crystalline diamond tools. The proposed method is expected to enable the ultraprecision machining of high-strength ceramic molds.

## 2. Tool-swinging cutting method

As shown in Fig. 1, a swinging movement is applied to a round-nosed diamond tool in diamond turning. The center of curvature of the cutting tool is adjusted to be in agreement with the center of rotation of the B-axis rotary table of the machine. By swinging the rotary table, the cutting point will constantly vary with respect to the tool edge during machining. As a result, the cutting time for a certain cutting point becomes very short and the temperature increase at this point will be dramatically reduced. In addition, the tool can be well lubricated as it swings, because lubricants can easily penetrate the tool-workpiece interface. In metal cutting, the cutting fluid enters the cutting zone as a result of the kinetic action of the capillary network in tool-chip interface and forms a boundary lubrication layer by physical and chemical adsorption onto the capillary wall [8]. However, when cutting high-strength ceramic materials, the tool-workpiece contact pressure is extremely high, so that the capillary network is hard to form, and the fluid cannot enter the cutting region. This situation, however, can be improved by rotary cutting [9]. The lubricant around the tool can penetrate both the rake face side and the flank face side as a result of the tool-swinging movement and enhances the lubrication effects. Based on the two aforementioned aspects, we expect that the tool-swinging cutting method will greatly improve the tool life in machining high-strength mold materials.

## 3. Experimental procedures

An ultraprecision lathe, NACHI-ASP15, was used in the experiments. Fig. 2 shows a schematic of the lathe. The lathe has an air-bearing spindle, two perpendicular linear tables ($X$- and $Z$-axes), and a rotary table (B-axis). The linear tables are supported by hydrostatic bearings and are driven by servomotors via hydrostatic screws. Laser hologram scales are used to position all of the tables, enabling a positioning resolution of 1 nm per step. The rotary table is also supported by high-stiffness hydrostatic bearings, and is driven by a friction drive in order to prevent backlash movements. These characteristics of the rotary table guarantee a high-accuracy tool-swinging movement. A three-dimensionally adjustable tool post was developed and placed on

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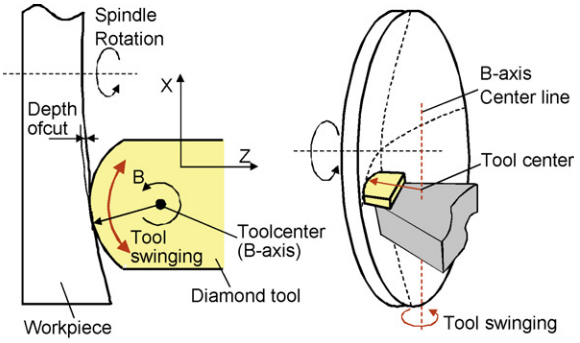


**Fig. 1.** Schematic diagram of the tool-swinging cutting method.

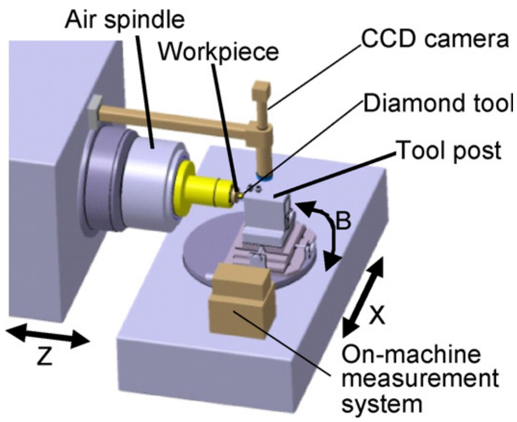


**Fig. 2.** Schematic diagram of experimental setup.

the B-axis rotary table. A three-component piezoelectric dynamometer, Kistler 9256C2, was embedded into the tool post to measure the cutting forces. A CCD microscope system was fixed above the diamond tool to observe and assist positioning of the tool. An on-machine profiling system, which has a repetitive measurement accuracy of 20 nm, was attached to the X-slide table in order to measure the cross-sectional profile of the machined surface.

Before cutting SiC, a copper workpiece was precut using the tool-swinging method. The tool-decentering error, namely, the error between the tool curvature center and the B-axis center, is detected from the cross-sectional profile of copper workpiece by the on-machine measurement system. The error data is then fed back to the numerical control program. In this way, the form error of the workpiece can be controlled in the sub-μm level.

The workpiece was reaction-bonded SiC having a diameter of 30 mm and a thickness of 10 mm. The elastic modulus, bending strength and hardness of the workpiece material are 407 GPa, 780 MPa, and 26.3 GPa, respectively. In the experiments, round-nosed cutting tools made of single-crystal diamond were used. All of the tools have the same nose radius (10 mm) and crystalline orientation. Three different rake angles, namely, 0°, −20°, and −40°, were used to examine the rake angle effect. The spindle rotation speed was set to 1000 rpm, the tool feed rate and the depth of cut were set to 20 μm/min and 2 μm, respectively. The tool-swinging speed was set to five levels, namely, 5°/min, 15°/min, 30°/min, 45°/min, and 60°/min by controlling the rotation speed of the B-axis table. As lubricants, kerosene mist and grease having a high $MoS_2$ micro-particle content were used, respectively. The grease was applied as a thin film on the workpiece surface.

## 4. Results and discussion

### 4.1. Effect of tool-swinging direction

Fig. 3 shows the effect of tool-swinging direction on surface roughness and cutting forces. For comparison, the results of conventional cutting without tool swinging were also plotted in the figure. In this experiment, the tool-swinging speed was set to 15°/min, and grease was used as lubricant. In Fig. 3, the cutting performance is remarkably improved through tool swinging, as compared with the conventional method. In addition, as shown in Fig. 3(a), the surface roughness of forward swinging cutting is remarkably better than that of backward swinging cutting. In Fig. 3(b), both the principal force and the thrust force of forward swinging cutting are smaller than those of backward swinging cutting.

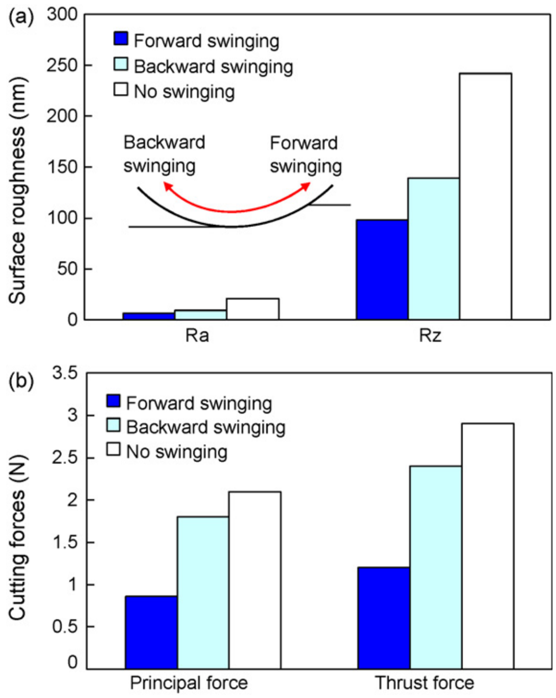


**Fig. 3.** Effects of tool-swinging direction on (a) surface roughness and (b) cutting forces.

As shown in Fig. 4, the undeformed chip thickness approaches zero near the tool tip, where the machining pressure is extremely high and the tool flank wear is the most severe. In forward swinging cutting, the lubricant on the left side of the tool could be easily brought into the tool tip region and reduce the tool wear in this region. In contrast, in backward swinging cutting, it is relatively difficult for the lubricant on the right side of the tool to reach the tool tip. Therefore, the lubrication performance in forward swinging cutting is better than that in backward swinging cutting, which leads to differences in surface finish and cutting forces.

### 4.2. Effect of tool-swinging speed

Fig. 5 shows the effect of tool-swinging speed on surface roughness and cutting forces. Forward swinging was adopted, and lubricant used was grease. As shown in Fig. 5(a), the surface roughness decreases with the increase in the swinging speed. As shown in Fig. 5 (b), the thrust force was decreased remarkably by increasing the tool-swinging speed, although the principal force

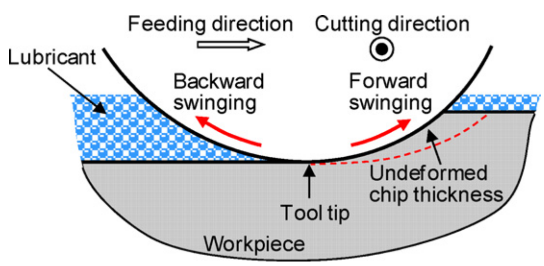


**Fig. 4.** Schematic model for lubrication in tool-swinging cutting.

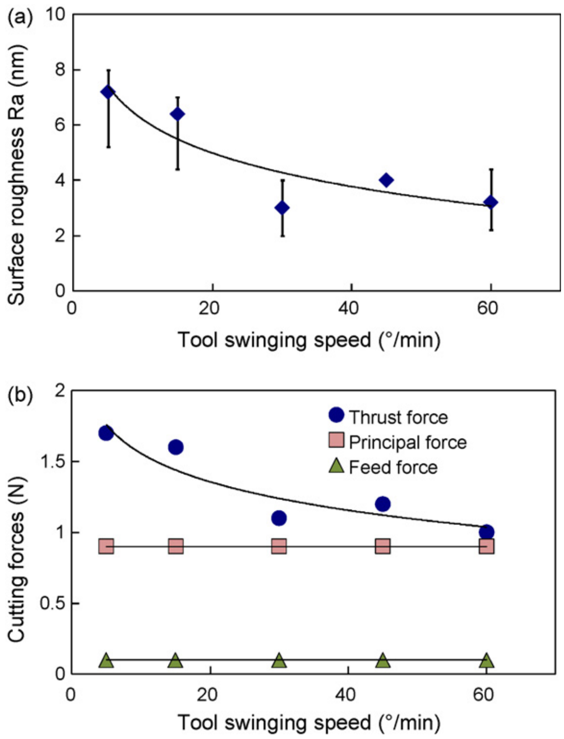


**Fig. 5.** Effects of tool-swinging speed on (a) surface roughness and (b) cutting forces.

and the feed force do not change noticeably. A higher tool-swinging speed can shorten the cutting time at a certain cutting point, reduce the temperature increase of the cutting edge, and bring a larger amount of lubricant into the cutting region, thereby enabling effective lubrication. This leads to a smaller flank wear land, and in turn, a better surface finish and a reduced thrust force.

### 4.3. Effect of lubricant type

To find suitable lubricants for the tool-swinging cutting method, kerosene mist and grease containing micro-sized $MoS_2$ particles were used as lubricants. The resulting flank wear land width (VB) was measured for each lubricant, and the results were compared. Fig. 6 shows the change in VB with the machined surface area. For all of the cases, VB increases with the machined surface area. However, the VB for the tool-swinging cutting method is remarkably smaller than that for the conventional cutting method without tool swinging. In addition, VB is smaller for the case in which grease was used as the lubricant, as compared to the case in which kerosene mist was used as the lubricant. Fig. 7 shows scanning electron microscope (SEM) micrographs of the cutting edge corresponding to data points A, B and C in Fig. 6. These SEM micrographs were taken at the tool tip as indicated in Fig. 4.

In the tool-swinging movement, the grease containing $MoS_2$ micro-particles is thought to have entered the tool-workpiece interface and to have formed a thin solid lubricant film, which could have improved the lubrication performance and protected the tool faces from high-pressure friction from the workpiece material. Therefore, other types of micro- to nano-particle-based

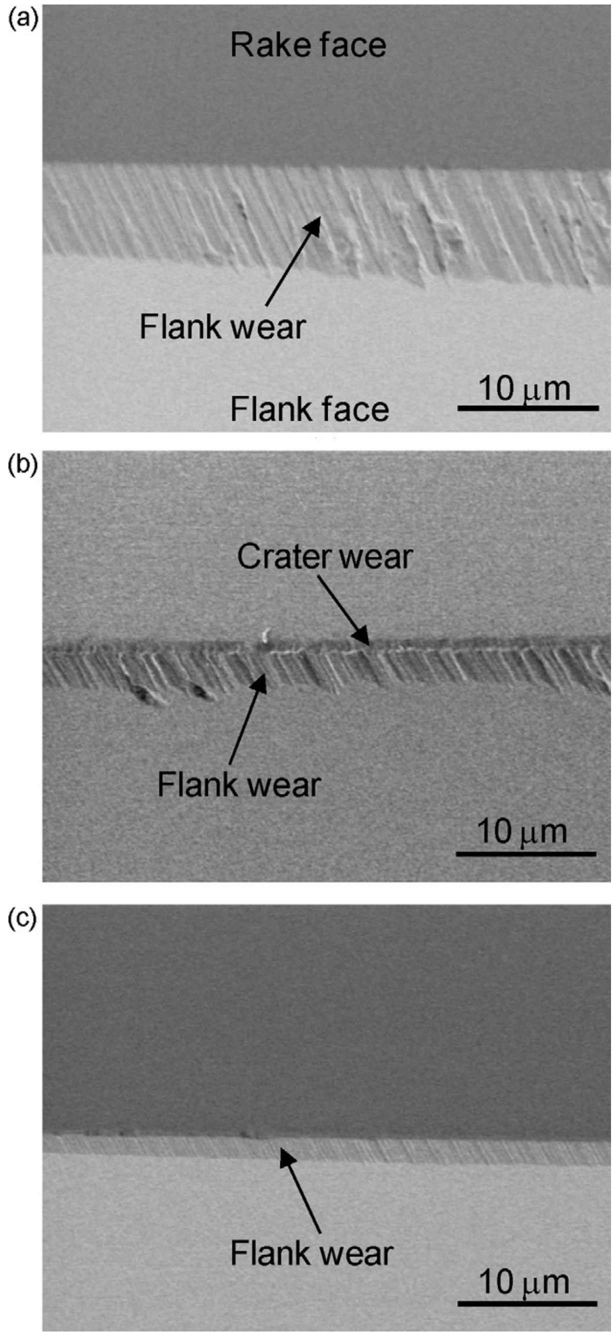


**Fig. 7.** SEM micrographs of the cutting edge corresponding to data points A, B, and C in Fig. 6.

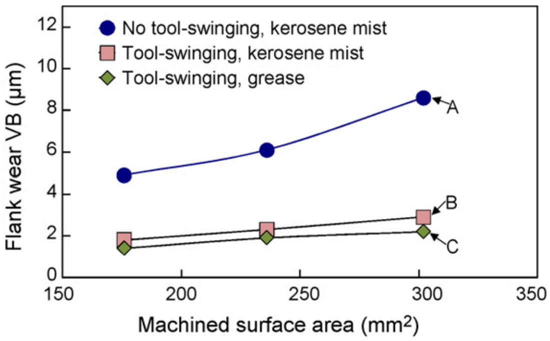


**Fig. 6.** Change in flank wear with respect to machined surface area.

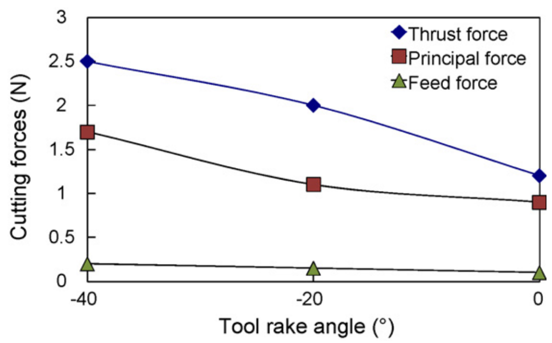


**Fig. 8.** Effect of tool rake angle on cutting forces.

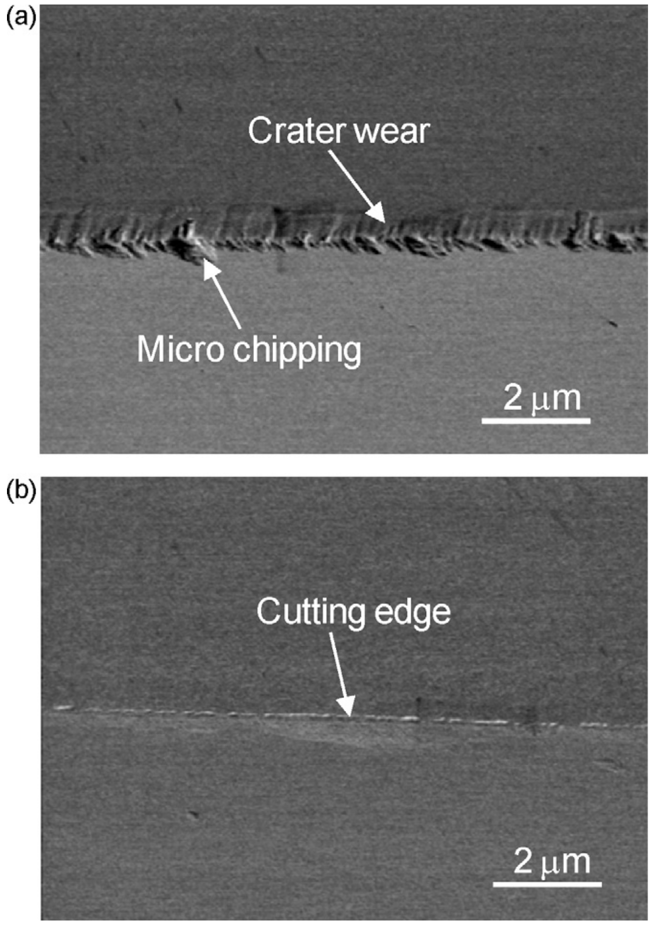


**Fig. 9.** SEM micrographs of the cutting edges of diamond tools having different rake angles: (a) 0° and (b) −40°.

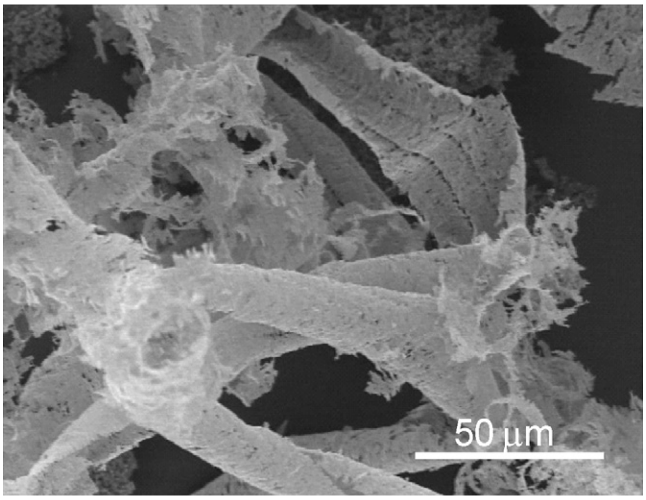


**Fig. 10.** SEM micrograph of cutting chips of reaction-bonded SiC.

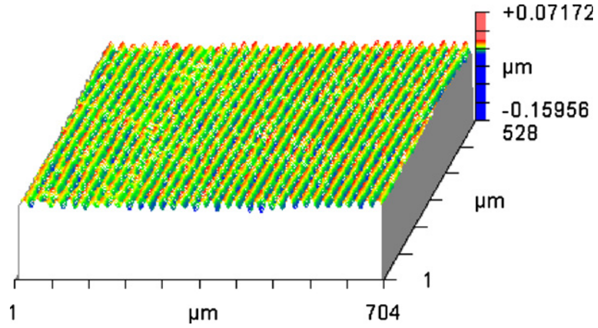


**Fig. 11.** Three-dimensional measurement result for surface roughness.

solid lubricants may be able to extend the service life of diamond tools in tool-swinging cutting of high-strength materials. This possibility is currently being investigated.

### 4.4. *Effect of tool rake angle*

Fig. 8 shows the effect of tool rake angle on cutting forces. In the experiments, forward tool swinging was used, and the swinging speed was 45°/min. The lubricant used was grease. The forces were measured at the early stage of cutting (machined surface area 84.8 $mm^2$). The cutting forces, especially the thrust force and the principal force, increase remarkably when the tool rake angle becomes highly negative. Fig. 9 shows SEM micrographs of the cutting edge of diamond tools having rake angles of 0° and −40°, respectively. As the tool rake angle becomes negative, micro-chippings and wear on the edge decrease significantly. Therefore, a negative rake angle improves the tool life, despite an increase in cutting forces.

### 4.5. *Material removal phenomenon*

Fig. 10 shows an SEM micrograph of cutting chips removed from the workpiece using a −40° rake angle tool. Other conditions were: forward tool swinging, swinging speed 60°/min, and feed rate 20 mm/min. The chips are of continuous type, indicating that the reaction-bonded SiC workpiece has been machined in a ductile manner, although it is a highly brittle material. Fig. 11 shows measurement results for surface roughness obtained using a white light interferometer ZYGO NewView 5000. The surface roughness of the machined workpiece is 4 nm Ra and 36 nm Ry. These results are comparable with those of lapping and polishing [2].

## 5. Conclusions

A tool-swinging cutting method was proposed and verified by ultraprecision diamond turning tests on reaction-bonded SiC. Due to the tool-swinging movement, tool wear was significantly suppressed, and the roughness of the machined surface was reduced. The use of a highly negative rake angle tool (∼−40°) and swinging the tool in the forward direction at high speed (>30°/min) are recommended. Grease containing $MoS_2$ micro-particles provided better lubrication than kerosene mist. In the test cuts, a surface finish of 4 nm Ra was obtained by generating continuous chips.

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