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*elliptical vibration cutting,*
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Hongjin JUNG[1*]
Eiji SHAMOTO[1]
Takashi UEYAMA[2]
Seiji HAMADA[2]
Liangji XU[3]

# MIRROR SURFACE FINISHING OF HARDENED DIE STEEL BY HIGH-POWER ULTRASONIC ELLIPTICAL VIBRATION CUTTING

Ultrasonic elliptical vibration cutting has recently been utilized in industry for finishing of various precision parts such as mirror surface finishing and precision micro machining of dies and molds. However, its application has been limited to high-cost ultra-precision machining, where depth of cut is typically in a range from a few micrometers to several tens of micrometers due to power limitation of the vibration device. To expand its application to low-cost mirror surface finishing with ordinary machining facilities, a high-power elliptical vibration device was developed in this research. The elliptical vibration cutting of hardened die steel was examined by applying the developed high-power elliptical vibration device with single crystalline diamond tools. Pick feed was kept to be 0.02 mm to obtain mirror quality surfaces, while depth of cut was increased up to 0.4 mm to verify performance of the high-power elliptical vibration cutting. By analyzing the experimental results, it was clarified that mirror surface finishing of the hardened die steel can be achieved at the large depth of cut with practically acceptable tool life.

## 1. INTRODUCTION

After elliptical vibration cutting was proposed firstly in 1994 [4], follow up studies have been carried out to demonstrate its performance [5],[10], to expand its applications [1],[6],[8] and to clarify its mechanics [2],[3],[7]. Especially, it was demonstrated from a practical viewpoint that the elliptical vibration cutting has superior performance in diamond cutting of hardened die steel, i.e. high quality surface finish, long tool life and low cutting force compared to conventional cutting methods [5]. The elliptical vibration cutting has also been applied successfully to micro/nano sculpturing of hardened die steel [8]. Recently, the elliptical vibration cutting technology has been utilized in practice to produce steel dies and molds mainly for optical parts.

[1] Nagoya University, Graduate School of Engineering, Japan
[2] Taga Electric Co., Ltd., Product Development Department, Japan
[3] The Boeing Company, Boeing Research & Technology, USA
[*] E-mail: jung@upr.mech.nagoya-u.ac.jp

The authors have also proposed mirror surface finishing of free form surfaces of dies and molds by the elliptical vibration cutting [6]. Compared to the conventional ball end milling, the elliptical vibration cutting has an advantage of the mirror quality surfaces. In addition to this great advantage, its machining efficiency can be higher than that of the ball end milling. Typically, feed speed needs to be as low as a few hundred mm/min in the ball end milling to obtain mirror quality surfaces, while it can be as high as a few thousand mm/min in the elliptical vibration cutting. This is because the vibration frequency can be much higher than the rotation frequency, and consequently the pitch of vibration marks is much smaller than the feed rate of milling.

However, the application of the elliptical vibration cutting technology has been limited to high-cost ultra-precision machining, because of power limitation of the commercially-available elliptical vibration device. Typically, depth of cut is set in a range from a few micrometers to several tens of micrometers when hardened die steel is machined. Hence, expensive machining facilities such as an ultra-precision machine tool and a temperature-controlled room are required to maintain the small depth of cut. On the other hand, there are much greater industrial needs for low-cost mirror surface finishing of dies and molds with ordinary machining accuracy than the high-cost ultra-precision machining. In the ordinary machining environment, machining error is often greater than one hundred micrometers mainly due to thermal deformation of machine tools [9]. Therefore, larger depth of cut than a hundred micrometers is desired in finishing. Otherwise, the displacement error may exceed the depth of cut, and some part of the surface may not be machined, which is not allowed in mirror surface finishing of dies and molds.

In order to realize the low-cost mirror-surface finishing of free-form surfaces of dies and molds, a high-power elliptical vibration device was developed in this research, and the developed high-power elliptical vibration device was applied to the elliptical vibration cutting of hardened die steel with single crystalline diamond tools. Its performance was examined at large depth of cut in terms of surface quality, cutting forces and tool wear.

## 2. DEVELOPMENT OF HIGH-POWER ELLIPTICAL VIBRATION DEVICE

The elliptical vibration device generally needs to have difficult characteristics, e.g. it must generate high-accuracy large-amplitude ultrasonic elliptical vibration against machining load, and it needs to be rigid enough to suppress the other vibrations including static displacement. The elliptical vibration is generated by combining two directional vibrations. Hence, the vibrator is designed to have the vibration modes in the two directions whose resonant frequencies and nodal positions are almost the same. Then, the two resonant vibration modes are excited while the vibrator is supported rigidly at the nodal positions [6].

In this research, there is an additional requirement of high-power. The power of ultrasonic vibration devices generally increases as volumes of the piezoelectric elements increase. Thus, larger piezoelectric elements were utilized in this study, which lead to low resonant frequency of about 16.9 kHz. It is considered that this frequency is the lower limit in practice since the elliptical vibration becomes too noisy for operators at further lower frequency. Meanwhile, a large device is not useful as a cutting tool, and thus the lowest 1st mode of longitudinal vibration was utilized to reduce the size as follows.

A high-power elliptical vibration device was designed based on the finite element analysis. Figure 1 shows results of the finite element analysis after some trials and errors. Fig. 1(a) shows the 1st mode of longitudinal vibration. The 3rd mode of bending vibration is combined as shown in Fig. 1(b). One of the challenges of this design is that the 1st longitudinal mode has only one vibration node, though the vibrator should be supported at plural nodal positions rigidly. Therefore, the vibrator was designed so that the resonant frequencies and the nodal positions (shown by yellow in Fig.1) are close to each other. The supports were designed so that the adjusted node of the two modes (shown by yellow) is supported rigidly in every direction and another node of the bending mode (shown by green) is supported flexibly in the longitudinal direction but rigidly in the lateral directions.
Fig. 2 shows the elliptical vibration of the developed device measured at the tool tip with laser Doppler vibrometers (Graphtec Corp., AT3700-AT0042). It demonstrates that the device can generate the elliptical vibration with an amplitude of about 10 $\mu m_{p\text{-}p}$ at about 16.9 kHz, which corresponds to the maximum vibration speed of about 32 m/min.

a) b)

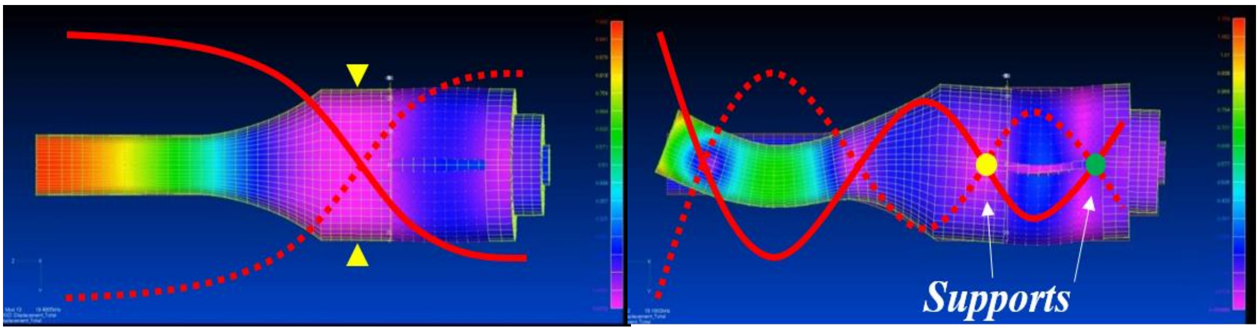



Fig. 1. Results of finite element analysis for high-power ultrasonic elliptical vibration device: a) 1st mode of longitude vibration (1/2λ), b) 3rd mode of bending vibration

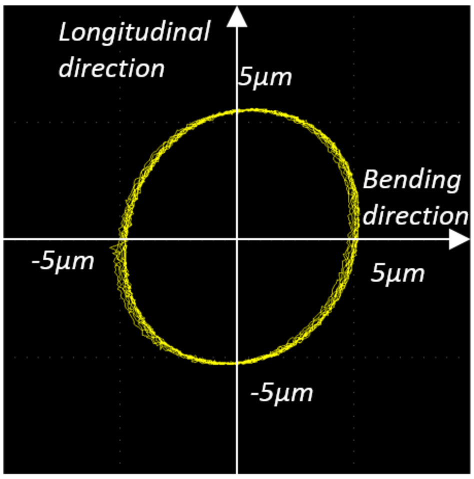



Fig. 2. Measured locus of elliptical vibration

## 3. EXPERIMENTAL SETUP AND CONDITIONS

### 3.1. FUNDAMENTAL PLANING EXPERIMENT

The cutting experiments were carried out on a precision machine tool (Nagase Integrex Co. Ltd., NIC-300) equipped with the developed high-power elliptical vibration device. Fig. 3 shows a photograph of the experimental setup and a schematic illustration of the cutting process.

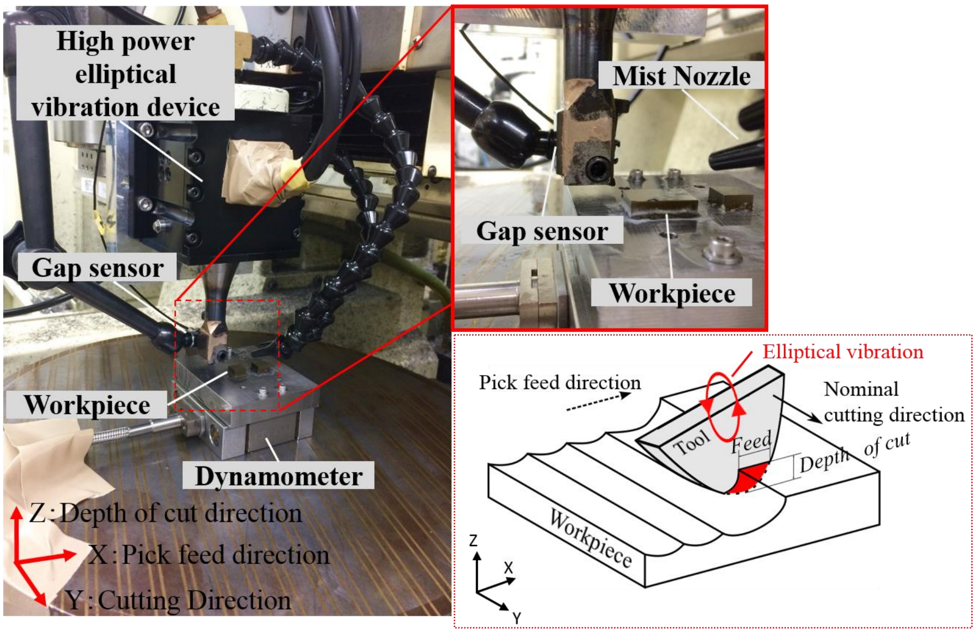



Fig. 3. Photograph of experimental setup (left) and schematic illustration of cutting process (lower right)

Typical hardened die steel (ISO: 4028-420-00-I, Stavax) was used as workpiece. A single crystalline diamond tool with a nose radius (*R*) of 1.0 mm was used to obtain mirror surfaces. Oil mist was supplied to the cutting point during the machining. Large depth of cut was set in a range from 0.1 mm to 0.4 mm not to leave unfinished surface, while pick feed (*f*) was set in a range from 0.005 mm to 0.020 mm to obtain mirror surfaces with theoretical roughness ($R_{th}$) of less than 0.050 μm. The experimental conditions are summarized in Table 1.

Table 1. Experimental conditions of fundamental planning experiment

| | |
|---|---|
| Workpiece | Material: Hardened die steel (ISO: 4028-400-00-I, Stavax)<br>Hardness: 53-54 HRC<br>Size : 10 mm ×10 mm |
| Diamond tool | Nose radius *R* (mm): 1.0 |

| | |
|---|---|
| | Rake angle : 0°<br>Clearance angle: 10° |
| Vibration conditions | Frequency (kHz): 16.9<br>Amplitude in cutting direction ($\mu m_{p\text{-}p}$): 10<br>Amplitude in depth of cut direction ($\mu m_{p\text{-}p}$): 10<br>Vibration locus: circle |
| Cutting conditions | Depth of cut (mm): 0.1, 0.2, 0.3, 0.4<br>Pick feed $f$ (mm): 0.005, 0.010, 0.020<br>Cutting speed (m/min): 1<br>Cutting fluid: oil mist |

### 3.2. TOOL LIFE TEST

A series of tool life test was also carried out in order to investigate influence of the large depth of cut on wear of a single crystalline diamond tool. The cutting conditions were kept constant at a depth of cut of 0.3 mm, pick feed of 0.005 mm and a cutting speed of 1 m/min respectively. A new single crystalline diamond tool was used throughout the test up to a nominal cutting distance of about 100 m. The experimental conditions are summarized in Table 2.

Table 2. Experimental conditions of tool life test

| | |
|---|---|
| Workpiece | Size: 10 mm × 50 mm |
| Cutting conditions | Depth of cut (mm): 0.3<br>Pick feed $f$ (mm): 0.005<br>Total cutting distance (m): 100 |
| Other conditions are the same as shown in Table 1. | |

## 4. EXPERIMENTAL RESULTS AND DISCUSSION

### 4.1. RESULTS OF FUNDAMENTAL PLANING EXPERIMENT

The cutting forces and the specific cutting forces measured during machining are plotted against cross-sectional area of the uncut chip in Fig. 4. It shows that the specific cutting forces, especially the thrust force, are decreased as the cross-sectional area of the uncut chip is increased. This indicates that roundness of the cutting edge causes size effect due to the edge force components even though the single crystalline diamond tool has a very sharp cutting edge. Considering high strength of the hardened die steel, the specific forces are very small especially at the large cross-sectional area and this implies that the developed elliptical vibration device works well against the large machining load at the large cross-sectional area or the large depth of cut.

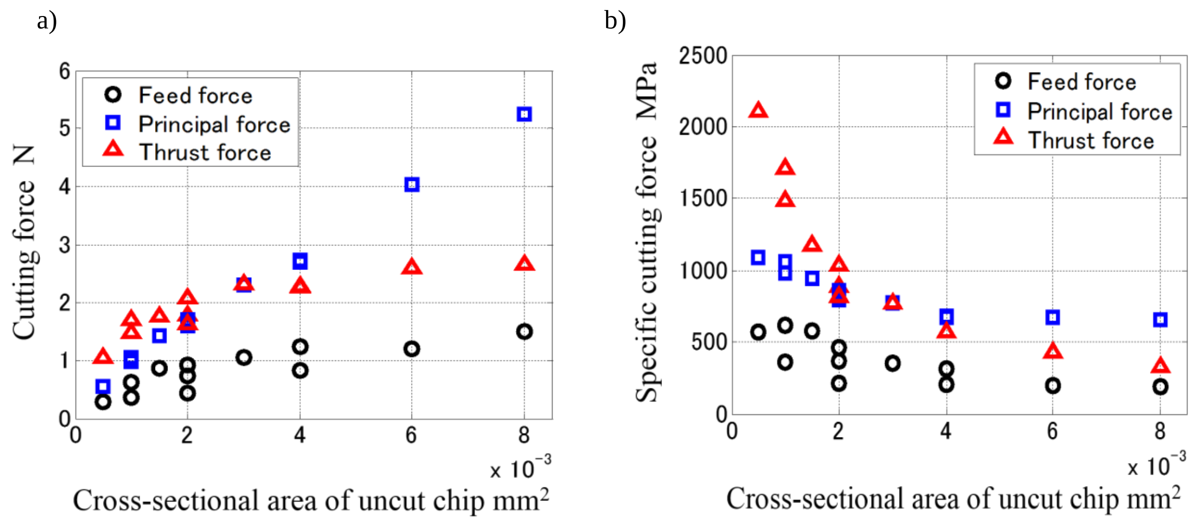



Fig. 4. Measured cutting forces (a) and (b) specific cutting forces against cross-sectional area of uncut chip

Fig. 5 shows a photograph of the machined surfaces. As shown, mirror quality surfaces can be obtained successfully even at large depth of cut of up to 0.4 mm. Figure 6 shows surface roughness measured in the pick feed direction with a stylus type surface roughness measuring instrument (Kosaka Laboratory Ltd., ET4000A) at various depth of cut and pick feed. As shown in the figure, roughness of the mirror surface obtained at a large depth of cut of 0.4 mm and a pick feed of 0.02 mm is 0.078 μm Rz or 0.013 μm Ra for example. It also shows that the surface roughness has positive correlation with the pick feed and the depth of cut. The effect of the pick feed can be understood by the theoretical roughness $R_{th} \approx f^2/(8R)$, i.e. $R_{th}$=0.003, 0.013, 0.05 μm when $f$=0.005, 0.01, 0.02 μm respectively, though Rz is always larger than $R_{th}$ especially at low pick feed. It is considered that this discrepancy and the effect of depth of cut are caused mainly by undesirable vibrations of the mechanical structures. These results imply that the surface quality may be further improved if the undesirable machine vibrations are reduced by using a better machine tool or developing a better high-power vibration device with higher accuracy and rigidity.

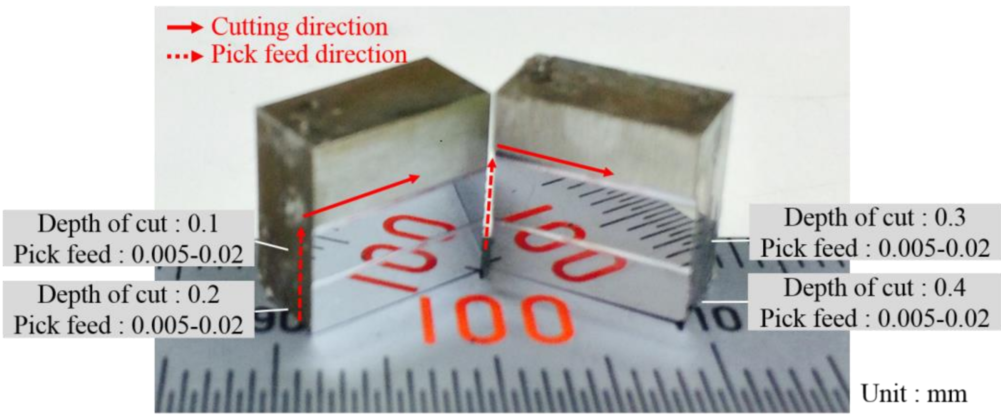



Fig. 5. Photograph of machined mirror surfaces

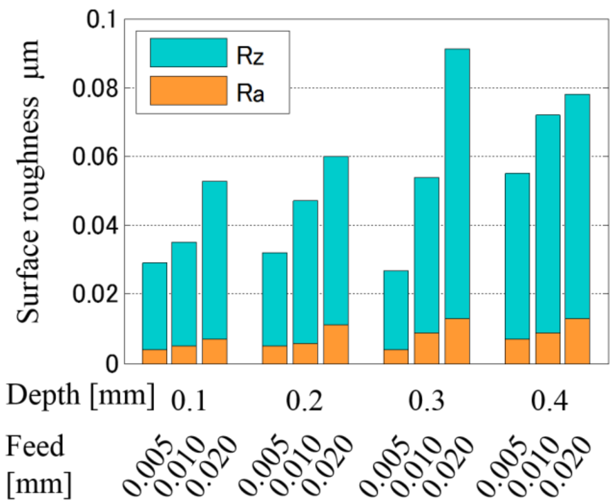



Fig. 6. Surface roughness measured at various depth of cut and pick feed

## 4.2. RESULTS OF TOOL LIFE TEST

The cutting forces measured during machining and the surface roughness measured in the pick feed direction after machining are plotted against cutting distance in Fig. 7. It shows that the cutting forces, especially the thrust force, increased as the cutting distance increased. It indicates that the tool wear increased gradually. Similarly to the above effect of the depth of cut on the surface roughness, the maximum height Rz increased with increasing cutting forces. On the other hand, the roughness average Ra was almost constant and less than 0.007 µm throughout the test.

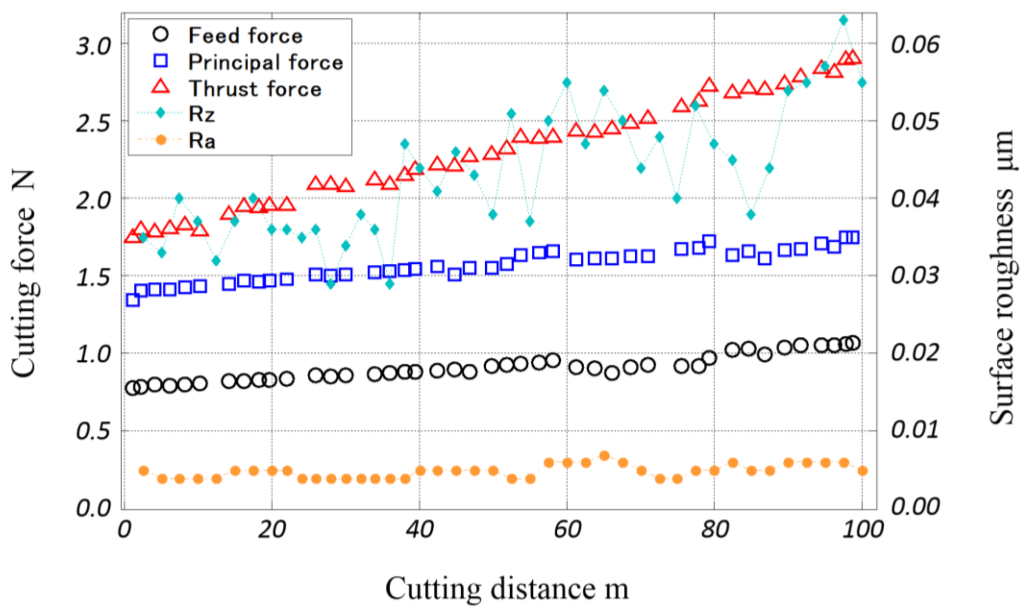
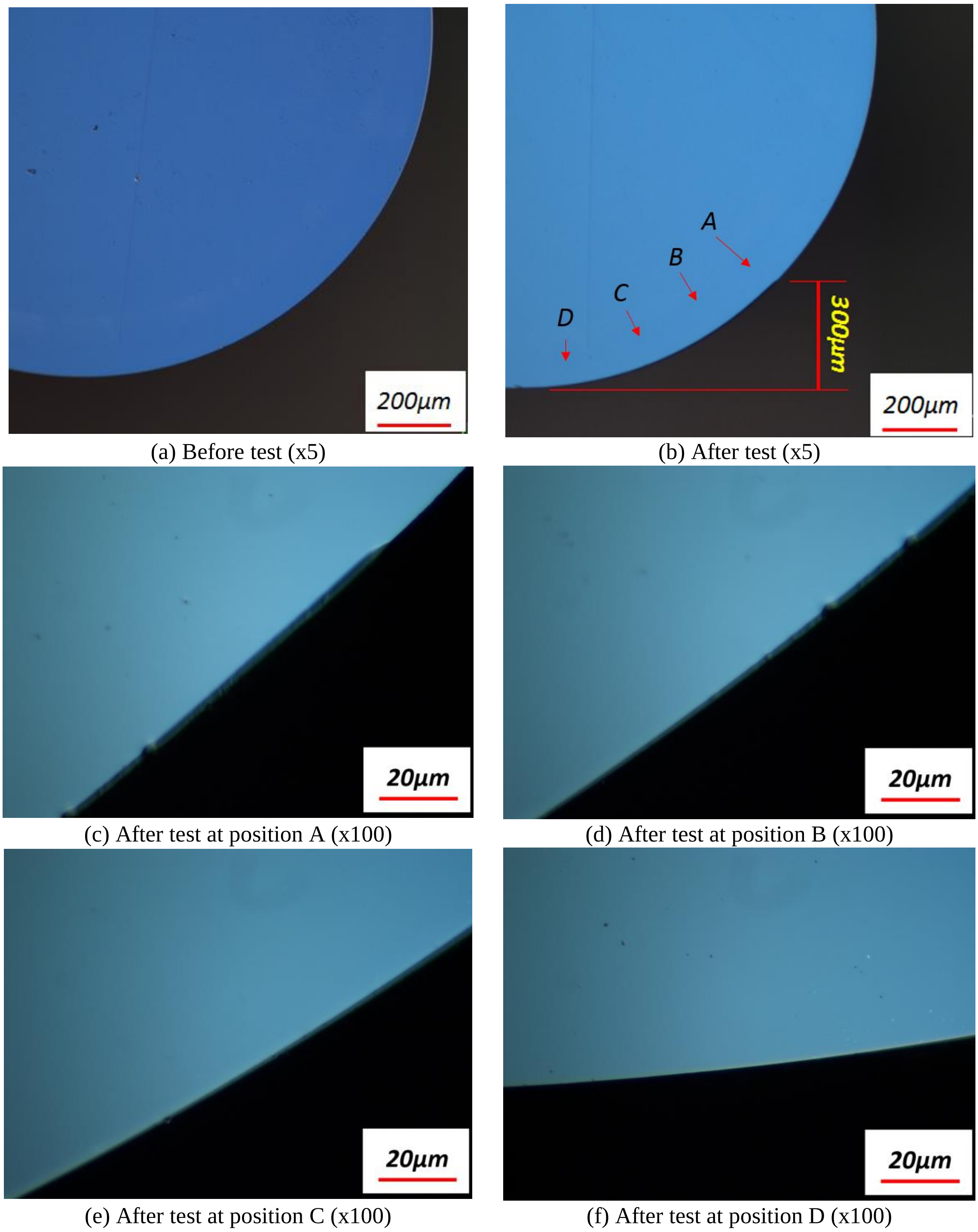



Fig. 7. Change of cutting forces and surface roughness against cutting distance

Fig. 8 shows microphotographs of the rake face of the single crystalline diamond tool. The microphotograph shown in Fig. 8(a) was taken before the test, while Fig. 8(b) after the test. Figs. 8(c) to (f) show close-ups taken at the positions A to D shown in Fig. 8(b) respectively. At the position A, small tool wear can be observed as shown in Fig. 8(c), whose width is about 2.8 μm.




(a) Before test (x5)
(b) After test (x5)
(c) After test at position A (x100)
(d) After test at position B (x100)
(e) After test at position C (x100)
(f) After test at position D (x100)

Fig. 8. Microphotographs of rake face of tool before and after tool life test

The tool wear is reduced as the measurement position moves to the bottom position D. This reduction of tool wear correlates with reduction of the uncut chip thickness shown schematically in Fig. 9.

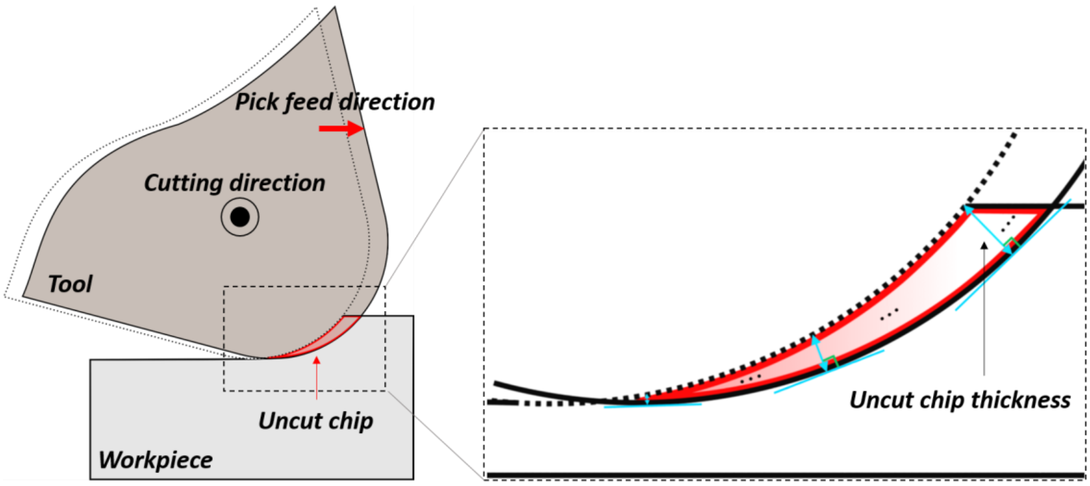



Fig. 9. Schematic illustration of uncut chip thickness along cutting edge (pick feed is exaggerated)

At the cutting edge position D, the tool wear is negligibly small and the uncut chip thickness is almost zero as shown in Figs. 8(f) and 9 respectively. The mirror quality surface was generated by this sharp cutting edge at D, and this may be the reason why the roughness average Ra was not increased against the cutting distance as shown in Fig. 7.

## 5. CONCLUSION

A high-power elliptical vibration device was developed in order to realize the low-cost mirror-surface finishing of free-form surfaces of dies and molds. The device was used in elliptical vibration cutting of hardened die steel with single crystalline diamond tools. Performance of the high-power elliptical vibration cutting was evaluated in terms of specific cutting forces, finished surface quality and tool wear. As a result, it was found that mirror quality surfaces with roughness of 0.013 μm Ra or less can be obtained even at a relatively large depth of cut of 0.4 mm. It was also found that the tool wear increases with the increasing of uncut chip thickness, and the roughness average Ra can be kept less than 0.007 μm at least up to a cutting distance of 100 m.

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