Paper:

Mirror Surface Machining of Steel by Elliptical Vibration Cutting with Diamond-Coated Tools Sharpened by Pulse Laser Grinding

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Low-cost mirror surface machining of die steel is proposed in this research by applying elliptical vibration cutting with diamond-coated tools sharpened by pulse laser grinding (PLG). It is well known that conventional diamond cutting cannot be applied to die steel owing to rapid tool wear. Several attempts have been reported to prevent rapid tool wear, such as using ultrasonic elliptical vibration cutting. The ultrasonic elliptical vibration cutting developed by the authors to achieve mirror surface finish on die steel and prevent rapid wear is widely used in the industry. However, high-cost single-crystalline diamond tools that are finished using a time-consuming lapping process are required to obtain mirror surfaces. The authors, meanwhile, have recently developed the PLG process to efficiently sharpen the cutting edges of hard tool materials such as cubic boron nitride. Therefore, a practical mirror surface machining method for die steel is proposed in this research, namely elliptical vibration cutting with low-cost diamond-coated tools sharpened by the efficient PLG process. The results of the machining experiments confirmed that practical mirror surface machining of die steel can be achieved by the proposed method.

Keywords: elliptical vibration cutting, pulse laser grinding, diamond-coated tool

1. Introduction

Mirror surface machining of die steel is desirable in the die and mold industry because polishing, which is still the most widely used method to obtain mirror surfaces, causes deterioration in form accuracy and increases the manufacturing time and cost. To achieve a mirror surface, the quality of the cutting tools – the cutting edge sharpness and form accuracy – is an important factor. Single-crystalline diamond tools, which can be made extremely sharp by lapping, are widely used for precision machining in the die and mold industry. However, it is well known that ferrous materials such as die steel cannot be machined easily owing to rapid tool wear [1–4]. Hence, the workpiece material for diamond cutting is generally restricted to electroless nickel, oxygen-free copper, plastics, and so forth [5]. Several attempts to prevent rapid tool wear have been reported. For example, nitriding of steels has been employed to reduce thermo-chemical tool wear [6]. Mirror surface machining of nitrided steels with single-crystalline diamond tools has been demonstrated. However, micro-chippings were observed on the cutting edge, which may be due to the presence of hard nitrogen compound particles in the outermost layer generated by the nitriding process [7].

Elliptical vibration cutting has also been employed to prevent rapid tool wear, and has realized mirror surface machining of die steels with single-crystalline diamond tools [8–11]. However, the high price of single-crystalline diamond tools is one issue that has prevented the widespread use of this cutting technology in the industry. Although the single-crystalline diamond has superior mechanical properties, the sharp cutting edge is produced by a time-consuming conventional lapping process, which increases its manufacturing cost. To achieve low-cost and high-precision machining of die steel, diamond-coated tools have been tested using elliptical vibration cutting. It has been confirmed that diamond-coated tools have superior wear resistance like single-crystalline diamond tools. However, the rough surface of the coated diamond layer makes it difficult to achieve a mirror surface finish on die steels [12]. A scanning laser beam was recently used to fabricate three-dimensional cutting edge on a single-crystalline diamond tool or a polycrystalline diamond tool [13, 14]. The authors have developed a new grinding method called pulse laser grinding (PLG) to sharpen the cutting edge of a tool, which can be applied to accurately and efficiently sharpen hard tool materials such as cubic boron nitride [15, 16]. To achieve low-cost mirror surface machining of hardened die steel, the PLG pro-

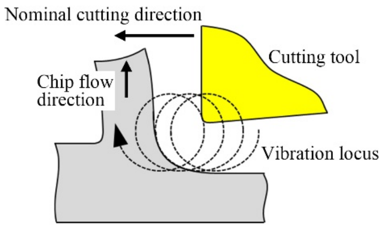

Fig. 1. Schematic illustration of elliptical vibration cutting.

cess was used to sharpen the cutting edge of the diamond-coated tool, and the cutting edge geometry of the sharpened tool was compared with that of a normal diamond-coated tool without sharpened cutting edge. Planing experiments were conducted on hardened die steel using both sharpened and normal diamond-coated tools, and the effect of PLG process was evaluated in terms of the cutting forces and surface roughness of workpieces. After carrying out basic planing experiments, tool life tests were also conducted by evaluating tool damages and surface roughness of workpieces.

2. Experimental Methods

2.1. Planing Experiments

Figure 1 shows the schematic illustration of the elliptical vibration cutting process. The tool was vibrated in an elliptical or circular locus and fed in the nominal cutting direction relative to the workpiece at the same time, so that the chip is formed intermittently and pulled out in each vibration cycle. The pulling force reduces or reverses the tool-chip friction force and decreases the chip thickness, cutting forces, and cutting energy. Consequently, tool wear is significantly reduced owing to the intermittent process and reduced energy. Since the change in the elliptical vibration amplitude directly affects the depth of cut, the vibration locus is precisely controlled [17].

The setup for the planing experiments is shown in **Fig. 2**. The elliptical vibration cutting device (Taga Electric, EL-50Σ) is equipped with an ultraprecision machine tool (Nagase Integrex, N2C-53US4N4). Two diamond-coated tools with a nose radius of 0.4 mm were used in this experiment, which are specially made as trial pieces by OSG Corporation. To achieve low-cost mirror surface machining of hardened die steel, the cutting edge of one tool was sharpened using the PLG process (sharpened diamond-coated tool). Details of the process will be presented in Section 2.3. Another diamond-coated tool without the PLG process (normal diamond-coated tool) was also tested for comparison. Owing to the cutting edge geometry of the sharpened tool, the elliptical vibration device was tilted in two directions as follows. The PLG process reduces the clearance angle to approximately 0°. To prevent rubbing of the flank face on the finished surface, the elliptical vibration device was tilted toward the nominal cutting direction at a lead angle of 10° to increase the clearance angle. The elliptical vibration device was also tilted toward the opposite direction to the pick feed to set the sharpened cutting edge parallel to the pick feed direction. Precise adjustment of the tilt angle is important for mirror surface machining because the sharpened cutting edge is straight in this experiment. The tilt angle was determined by conducting preliminary grooving experiments on oxygen-free copper workpiece. As a result, the tilt angle was set to 41°.

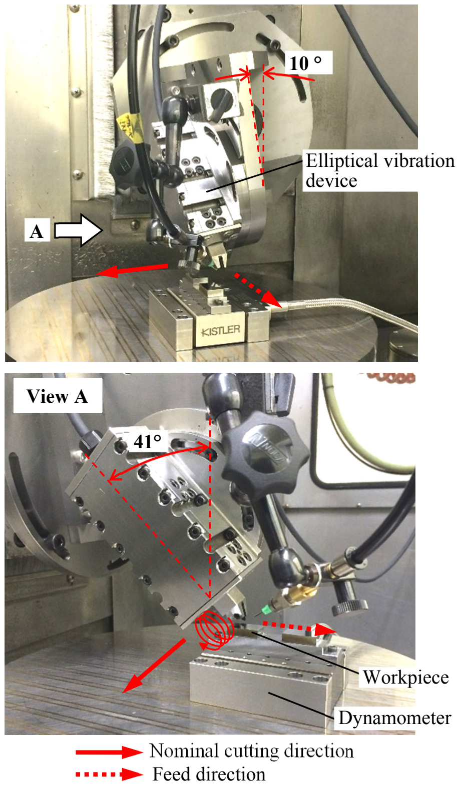

Fig. 2. Setup for planing experiments.

After adjusting the lead and tilt angles of the elliptical vibration device, planing experiments were conducted using sharpened/normal diamond-coated tools. The cutting tools vibrate in a circular locus at a frequency of approximately 40 kHz and an amplitude of 4 $\mu m_{p\text{-}p}$. A typical hardened die steel, Stavax (modified AISI 420) with hardness of 54 HRC was used for the workpieces. The dimension of the workpieces was 20 × 13 mm and they were fixed on a dynamometer (Kistler, 9256C). The coolant (Fuji BC Engineering Co., Ltd. Bluebe LB-10) was supplied to the cutting point with compressed air through a mist nozzle. The cutting conditions are summarized in **Table 1**. An optical surface profiler (Zygo, NewView7300) was used to measure the surface roughness of the workpieces.

2.2. Tool Life Tests

Tool life tests were also conducted on the same workpiece material (Stavax) using elliptical vibration cutting with the two types of diamond-coated tools, namely

Table 1. Cutting parameters and vibration parameters.

Cutting parameters for fundamental experiments	
Depth of cut [μm]	20
Pick feed [μm]	5,10, 20, 40, 60, 80
Cutting speed [m/min]	1
Coolant	Oil mist (Bluebe LB-10)
Vibration parameters	
Frequency [kHz]	Approximately 40
Amplitude [$\mu m_{p\text{-}p}$]	4
Phase shift [deg.]	90 (circle)

Table 2. Cutting parameters for tool life experiments.

Depth of cut [μm]	50
Pick feed [μm]	5
Cutting speed [m/min]	1
Coolant	Oil mist (Bluebe LB-10)

sharpened diamond-coated tool and normal diamond-coated tool without sharpened cutting edge. The tilt and lead angle of the elliptical vibration device were adjusted using the procedure described in the previous section. The size of the workpiece was 100 × 100 mm, and planing experiments were continued until the nominal cutting distance reached 616 m (for normal tool) and 640 m (for sharpened tool). The cutting conditions of the tool life tests are summarized in **Table 2**. The roughness of the finished surfaces was measured using an optical surface profiler (Zygo, NewView7300), and tool damages were observed using a scanning electron microscope (FEI Quanta400).

2.3. Sharpening Process by PLG

The cutting edge of the diamond-coated tool was sharpened by the PLG process. **Fig. 3** shows a photograph of the experimental setup. The device has three linear axes (X, Y, Z) and two rotary axes (A, C). A pulse laser source and a work table were fixed on the Z-axis and the A-axis, respectively. The pulse laser was irradiated on the cutting edge of the diamond-coated tool fixed on the work table. The optical axis of the PLG process was adjusted to the cutting edge based on the optical image obtained through the lens, which was used in the PLG process. To flatten the surface of the cutting tool, the cutting tool was moved five times along the X-axis to scan the laser beam.

Figure 4 shows a schematic illustration of the PLG process, and the conditions are summarized in **Table 3**. The cutting edge was sharpened on both the rake face side (**Fig. 4(a)**) and the flank face side (**Fig. 4(b)**). The laser beam irradiation angle and the scanning direction against the flattened surface are key factors in terms of the flattening efficiency and surface quality. The surfaces to be

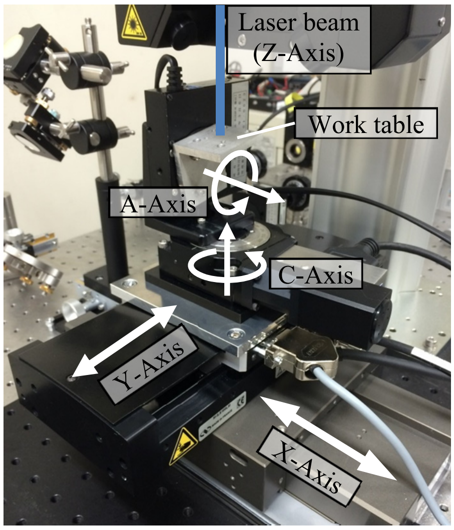

Fig. 3. Photograph of experimental setup for PLG process.

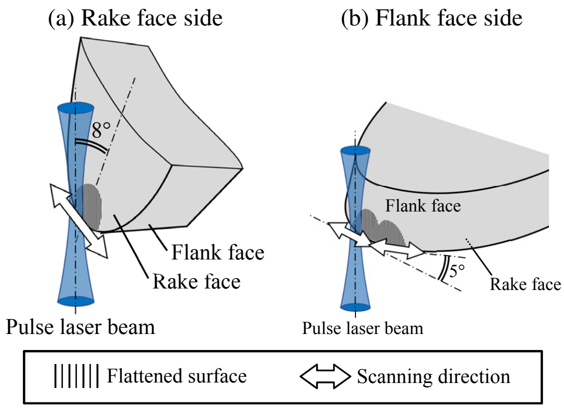

Fig. 4. Setup for planing experiments.

Table 3. Pulse laser grinding conditions.

Wave length [nm]	355
Pulse length [ns]	5
Frequency [Hz]	15000
Power [W]	2.8
Spot diameter [μm]	20
Power density [GW/cm^2]	11.8
Scanning speed [mm/s]	30
Number of scanning [times]	5

sharpened were irradiated with a pulse laser beam whose incident angle was considerably small, namely 8°, and the linear scan movement was directed along the cutting edge to flatten the surface. Considering the acceleration of the linear stage, the scan length was set to be long so that PLG is carried out after the scanning speed reaches the desired value. Because the laser beam is almost parallel to the machined surface, this technology is advantageous in terms of finishing of smooth surfaces compared to conventional laser machining technologies. The maximum depth of

PLG was controlled within the thickness of the diamond-coating layer, which was estimated to be approximately 10 μm. To form a V-shaped cutting edge, the scan movement on the flank face was set in two directions, which crossed each other at an angle of 5°. Since the surfaces are flattened with a slight obliquity with respect to the original surfaces, the actual rake angle becomes slightly negative, and the clearance angle approaches zero. The small clearance angle requires an inclination of the vibration device to prevent rubbing of the flank face as described in Section 2.1. The cutting edge was observed, and its geometry was measured using the scanning electron microscope (FEI, Quanta400) and the optical surface profiler (Zygo, NewView7300), respectively.

It is expected that the PLG process will also be applied to round nose cutting tools for future work. To sharpen the round nose cutting edges, the laser beam should be scanned along the curved flank faces of the cutting tools, which requires rotary motion of the cutting tool. The centering accuracy of the tool nose on the rotary table is assumed to be a key factor.

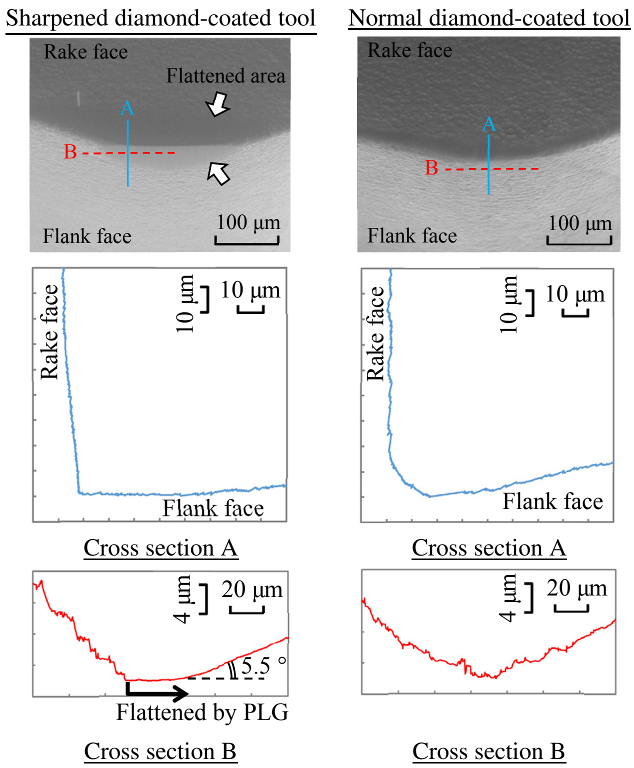

Fig. 5. Setup for planing experiments.

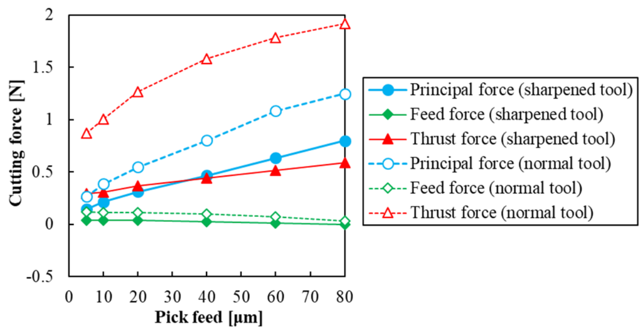

Fig. 6. Cutting forces measured at various pick feeds.

3. Results and Discussions

3.1. Change in Cutting Edge Geometry by PLG Process

Figure 5 shows SEM images of the two types of diamond-coated tools: sharpened tool and normal tool. The flattened areas of the rake and flank faces indicated by white arrows are smoother than the original surfaces, and the cutting edge is sharper. To clarify the geometries of the cutting edges, the cross sections were measured in two directions using the optical surface profiler, that is, cross sections A perpendicular to the cutting edges, and cross sections B parallel to the cutting edges. Approximate measurement lines of cross sections A and B are indicated by solid lines and dotted lines on the SEM images, respectively. It can be observed that the radius of the cutting edge roundness was significantly decreased by the PLG process from more than 10 μm to 1 μm or less. Cross sections B represent the geometries of the flank faces. Although it is difficult to measure the cross sections that will be engaged with the workpieces, the surface quality of the flank faces is important for precision machining. The results show that two flat smooth surfaces were generated on the flank face of the sharpened diamond-coated tool, and they cross each other at the set angle of approximately 5°. On the other hand, micron-order asperities were observed in cross section B of the normal diamond-coated tool. Thus, a mirror surface finish can be expected only with the sharpened diamond-coated tool.

3.2. Results of Planing Experiments

Figure 6 shows the cutting forces measured at various pick feeds listed in **Table 1**. Compared with the normal diamond-coated tool, all cutting force components of the sharpened diamond-coated tool decreased at each pick feed. In particular, the feed forces and the thrust forces of the sharpened diamond-coated tool decreased to approximately one-third of those of the normal diamond-coated tool, although the nominal rake angle of the sharpened tool was smaller than that of the normal tool. This significant reduction is attributed to the small cutting edge roundness of the sharpened diamond-coated tool. Moreover, the feed force acting on the sharpened diamond-coated tool at a pick feed of 80 μm represents a slightly negative value of -0.005 N, which indicates that the feed force is acting in such a manner that the cutting tool pulls the workpiece (each cutting force represents the average of five values, and each value of the feed force at the aforementioned cutting condition represents a negative value from -0.011 to -0.002 N). This is because the tilt angle of 41° provides a chip pulling force in the pick feed direction as well as in the thrust direction.

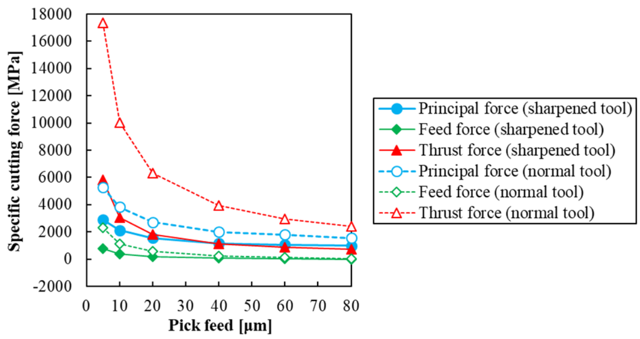

Fig. 7. Specific cutting forces measured at various pick feeds.

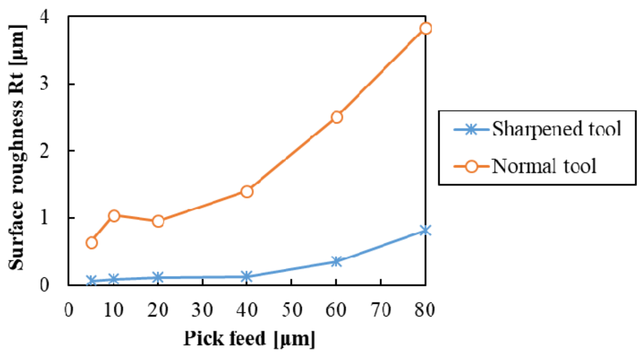

Fig. 8. Surface roughness *Rt* measured at various pick feeds.

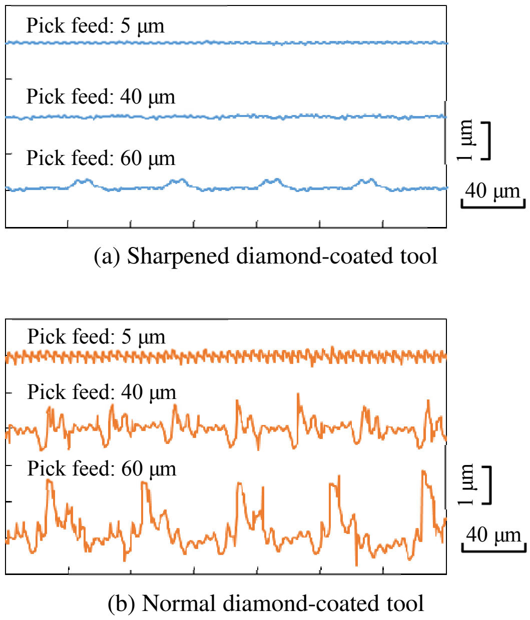

Fig. 9. Profiles of finished surfaces at typical pick feeds of 5, 40, and 60 μm obtained with (a) sharpened diamond-coated tool, and (b) normal diamond-coated tool.

Figure 7 shows the specific cutting forces calculated by dividing the measured cutting forces by the depth of cut and the pick feed. The highest thrust force of 17400 MPa was measured with the normal diamond-coated tool. This is because the large cutting edge roundness increases the ploughing area on the cutting edge where the material flows downward without chip formation and elastic/plastic deformation occurs under the cutting edge [18]. When the pick feed increased, the specific cutting forces decreased exponentially. The principal, feed, and thrust forces of the sharpened diamond-coated tool decreased and converged to 1000, −5.7, and 740 MPa, respectively.

Figure 8 shows the surface roughness *Rt* of the cut surfaces plotted against the pick feeds. The surface roughness obtained with the sharpened diamond-coated tool is significantly smaller compared to that obtained with the normal diamond-coated tool at each pick feed. The smallest surface roughness of 0.07 μm was achieved with the sharpened diamond-coated tool at the pick feed of 5 μm. In addition, the surface roughness was less than 0.14 μm until the pick feed increased to 40 μm, while that obtained with the normal diamond-coated tool increased from 0.64 to 1.40 μm and finally to 3.83 μm with increasing pick feed.

To clarify the difference in the surface roughness, the surface profiles of the finished surfaces at typical pick feeds of 5, 40, and 60 μm are shown in **Fig. 9**. Smooth surfaces were produced with the sharpened diamond-coated tool at pick feeds of 5 and 40 μm, while periodic asperities appeared at the pick feed of 60 μm. As shown in **Fig. 5**, the flank face was flattened by the PLG process, and a straight cutting edge, with a length of approximately 40 μm, was generated. Hence, a large pick feed exceeding the cutting edge length (e.g., 60 μm) results in asperities, whose cycle corresponds to the pick feed. In other words, by extending the straight cutting edge length prepared by the PLG process, higher efficiency mirror surface machining can be achieved by increasing the pick feed within the extended cutting edge length.

As shown in **Fig. 9(b)**, rough surfaces were obtained with normal diamond-coated tool, which is possibly due to the micron-order asperities on the flank face as shown in **Fig. 5**. Although the pick feed decreased to 5 μm, higher periodic asperities were observed on the surface profile. The periodic asperities are partly attributed to burrs generated in each cutter path. Owing to the large cutting edge roundness of more than 10 μm as mentioned in Section 3.1, the actual rake angle under experimental cutting conditions is considered to be negative, and burrs occurred as a result of this negative rake angle.

Photographs of the workpieces finished by both the sharpened diamond-coated tool and normal diamond-coated tool are shown in **Fig. 10**. Letters were visibly reflected on the surface finished by elliptical vibration cutting with sharpened diamond-coated tool at pick feeds of 5 to 40 μm. The reflections were blurred with increasing surface roughness at pick feeds of 60 and 80 μm. This trend agrees well with the measured surface roughness. On the other hand, only blurred reflections were observed on the surface finished with normal diamond-coated tool, even when the pick feed was reduced to 5 μm.

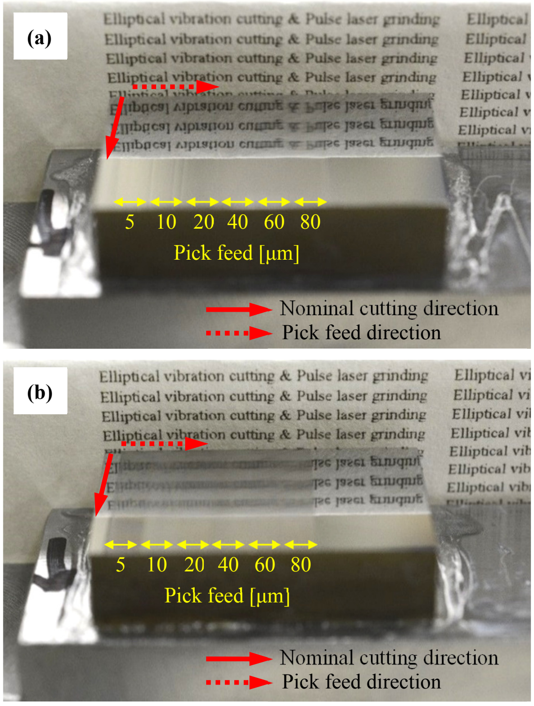

Fig. 10. Workpieces of typical hardened die steel, Stavax (size: 20 × 13 mm, hardness: 54 HRC) finished with (a) sharpened diamond-coated tool, and (b) normal diamond-coated tool.

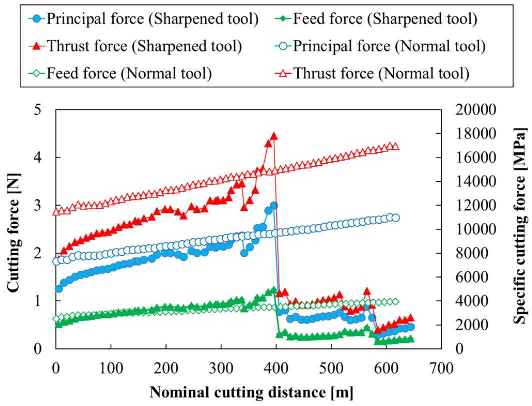

Fig. 11. Cutting forces and specific cutting forces in tool life experiments.

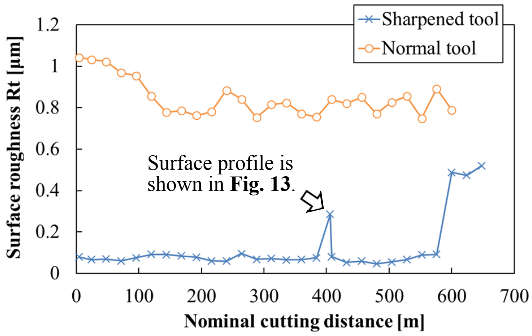

Fig. 12. Surface roughness *Rt* plotted against nominal cutting distance.

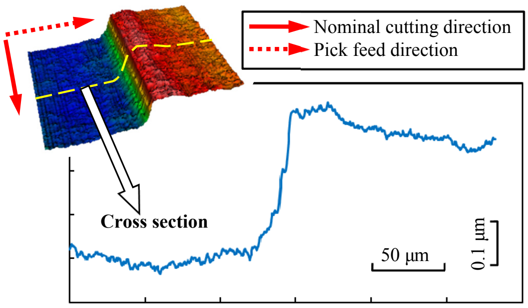

Fig. 13. Surface profile of workpiece finished with sharpened diamond-coated tool in tool life test (measurement point: nominal cutting distance of 405 m).

3.3. Results of Tool Life Tests

Figure 11 shows measured cutting forces plotted against nominal cutting distance during the tool life tests. The secondary vertical axis of the graph represents the specific cutting forces. The cutting force components measured with the normal diamond-coated tool constantly increased, which indicates that significant damages such as chippings did not occur on the cutting edge of the normal diamond-coated tool. In contrast, the cutting forces in the sharpened diamond-coated tool varied with the increase in the nominal cutting distance. The initial values of the principal and thrust forces of the sharpened diamond-coated tool are approximately two-thirds as small as those of the normal diamond-coated tool. However, the cutting forces gradually increased, and were finally greater than those of the normal diamond-coated tool at the nominal cutting distance of 100 m (for the feed force) and 370 m (for the principal and thrust forces). All cutting force components of the sharpened diamond-coated tool suddenly dropped to less than 1.2 N at the nominal cutting distance of 405 m, and then constant low cutting forces were observed. The sudden drop in the cutting forces are due to a drastic change in the cutting edge of the sharpened diamond-coated tool.

The surface roughness *Rt* of the finished surfaces is plotted against the nominal cutting distance in **Fig. 12**. As described in Section 3.2, the surface roughness obtained with the normal diamond-coated tool is in the range of 0.7–1.1 μm, which is much larger than that with the sharpened diamond-coated tool. The surface roughness obtained with the sharpened diamond-coated tool is maintained to be less than 0.1 μm, except a point measured at the nominal cutting distance of 405 m. The surface profile of the finished surface at this point is shown in **Fig. 13**. A micro step with a height of approximately 0.4 μm was observed in the pick feed direction. It can be expected that micro-chipping occurred on the sharpened cutting edge, which results in the reduction of the cutting area as well as the sudden drop in the cutting forces observed at the nominal cutting distance of 405 m. Although micro-chipping is thought to occur, the surface roughness after this point is less than 0.1 μm until the nominal cutting distance of 570 m. This implies that the micro-chipping area on the

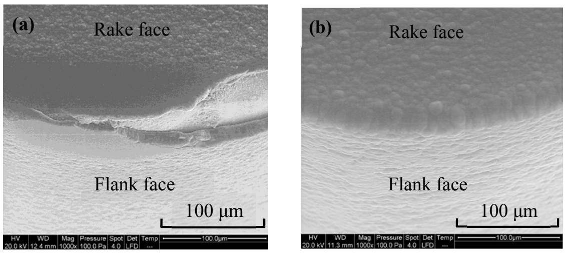

Fig. 14. SEM images of diamond-coated tools after tool life tests. (a) Sharpened tool, (b) normal tool.

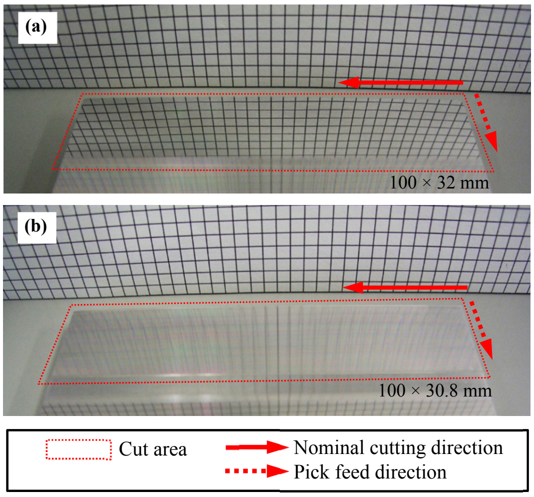

Fig. 15. Photographs of workpieces used in tool life tests cut by (a) sharpened diamond-coated tool, (b) normal diamond-coated tool.

sharpened cutting edge is sufficiently small to maintain mirror surface machining of the workpiece, and that the cutting edge becomes sharp due to chipping to reduce the cutting force.

Figure 14 shows SEM images of the cutting edges after tool life tests. Delamination of diamond can be observed on the sharpened cutting edge (see **Fig. 14(a)**). It is considered that delamination occurred at the nominal cutting distance of 570 m at which the surface roughness increased from 0.09 to 0.49 μm as shown in **Fig. 12**. On the other hand, significant wear or chipping did not occur in the normal diamond-coated tool (see **Fig. 14(b)**). This result indicates that the diamond coating has high wear resistance against hardened die steel when elliptical vibration cutting is applied.

Photographs of the finished surfaces are shown in **Fig. 15**. A clear reflection is obtained only on the surface cut with the sharpened diamond-coated tool. Hence, it is demonstrated that the proposed cutting technology, that is, elliptical vibration cutting with PLG-sharpened diamond-coated tools, can realize mirror surface machining of hardened die steel. The next challenge is expected to be the suppression of delamination.

4. Conclusions

Elliptical vibration cutting with PLG-sharpened diamond-coated tools was proposed for practical low-cost mirror machining of hardened die steel. The result of the PLG process on elliptical vibration cutting performance was compared with that of normal diamond-coated tool by measuring the cutting edge geometries, cutting forces, and roughness of the finished workpiece surfaces during planing experiments. The results can be summarized as follows:

1) The rake and flank faces of the diamond-coated tool can be precisely and efficiently sharpened by the PLG process, which results in a small cutting edge roundness of a micron or less. The cutting forces were reduced by using the PLG-sharpened diamond-coated tool. In particular, the feed and thrust forces of the PLG-sharpened diamond-coated tool were reduced to approximately one-third of the values obtained with the normal diamond-coated tool.

2) Mirror quality surface finish was achieved with the smallest surface roughness of 0.07 μm *Rt* with the sharpened diamond-coated tool at a pick feed of 5 μm. The surface roughness was reduced to approximately one-ninth of the value obtained with the normal diamond-coated tool under the same conditions.

3) Owing to the straight cutting edge generated by the PLG process, the surface roughness was maintained to be less than 0.14 μm, if the pick feed does not exceed a cutting edge length of approximately 40 μm.

4) It was clarified from the tool life tests that mirror surface machining of hardened die steel can be realized up to the nominal cutting distance of 570 m using PLG sharpened diamond-coated tool; however, it is possible that micro-chipping occurred during the tool life test.

Acknowledgements

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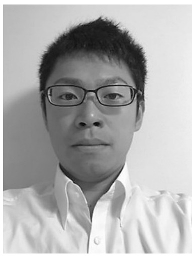

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