Ultraprecision sculpturing of hardened steel by applying elliptical vibration cutting

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Abstract – Elliptical vibration cutting technology is well-known for its excellent performance in ultraprecision machining of steel materials with single crystal diamond tools. This paper presents two approaches to attain high-performance micro- and macro-scale sculpturing for steel materials by utilizing elliptical vibration cutting. In order to attain free-form sculpturing in macro-scale, a 4-axis controlled machining method has been proposed. An ultrasonic elliptical vibration system for the proposed method was developed and experimental verifications were conducted. A novel micro/nano-scale sculpturing method was also introduced. In this method, a depth of cut is actively controlled in elliptical vibration cutting by controlling vibration amplitude in the vertical direction. By utilizing this as a fast tool servo function, high performance micro/nano sculpturing of steel materials can be attained directly by single crystal diamond tool without using conventional fast tool servo technology. A practical sculpturing system was developed and applied to various applications, such as textured grooving, picture image machining and dimple pattern sculpturing.

Key Words**:** cutting, ultraprecision cutting, elliptical vibration cutting, sculpturing, difficult-to-cut material

1. Introduction

Hardened steel is often used as mold materials in manufacturing industry. Some of them are required to have mirror surface quality and sophisticated free-form shape simultaneously. Ultraprecision cutting technology is generally useful to attain such mirror surface sculpturing. By utilizing a sharp single crystal diamond tool and an ultraprecision machine tool, arbitrary micro and macro structures can be machined with mirror surface quality. However, conventional diamond cutting is not applicable directly to steel materials due to extremely rapid tool wear and surface deterioration. Therefore, Nickel-phosphorous (NiP) electroless plating is generally applied on the steel mold surfaces, and only thin NiP plating layer is machined by the single crystal diamond tool with less tool wear[1)]. Otherwise, polishing needs to be applied as a finishing process following the sculpturing of the steel molds by conventional machining methods, such as end milling, grinding and electric discharge machining. Both conventional methods result in a decrease in efficiency and an increase in cost. The polishing can also cause surface shape deterioration, especially at sharp edges. So, reduction of these processes in mold manufacturing has been a major focus of production engineering in industry. And thus, a number of researchers have dedicated to attain diamond machining of steel materials[2), 3)].

Moriwaki and Shamoto have applied ultrasonic vibration into the ultraprecision cutting of the steel materials, and it was verified that ultrasonic vibration cutting can be effective to decrease the tool wear and to attain mirror surface machining of the steel material directly by single crystal diamond tool[4)]. Shamoto has extended conventional linear vibration cutting to elliptical vibration cutting[5)], and investigated its superior cutting performances[6)]. In elliptical vibration cutting, the tool is vibrated elliptically and fed in the nominal cutting direction relatively to the workpiece simultaneously, so that the chip is formed intermittently and pulled out in each vibration cycle. Since the friction between the chip and the tool rake face is drastically reduced or reversed, the shear angle is increased. Consequently, the cutting force and the cutting energy are reduced significantly. The intermittent cutting process at an ultrasonic frequency is also effective in preventing the tool wear and the adhesion, and thus, diamond cutting of hardened steel can be realized as reported in the past literatures[7)].

While elliptical vibration cutting is beneficial in various aspects, there is also a disadvantage, i.e., a cutting speed is restricted to be relatively lower than the vibration speed. Because of this restriction, the vibration speed is generally limited to be less than about 5 m/min in practice. Its machining time, consequently, becomes longer in some cases as compared with the conventional methods. However, machining efficiency can be increased contrarily when it is applied to sculpturing. The present paper summarizes novel high-performance sculpturing methods in micro- and macro-scale by applying elliptical vibration cutting and their applications.

2. Macro-scale sculpturing by applying elliptical vibration cutting

Figure 1 shows the proposed mirror surface finishing method. The tool is supposed to be vibrated elliptically in the desirable plane, and it is fed along the sculptured surface while the relative rotational position between the tool and the workpiece is precisely controlled in accordance with the sculptured surface orientation as shown in the figure. The conventional and proposed methods are compared in Fig. 2. In the proposed method, the tool is not rotated at the constant speed, unlike conventional rotating end mills, but the rotational position of the tool is precisely controlled. Thus, the proposed method needs a precision machine tool with at least 4 axes, i.e., X, Y, Z and C, to machine the sculptured surfaces, while the conventional end milling can be operated with 3-axis controlled machine tool. Both the elliptical vibration cutting and the end milling processes are intermittent, but the vibration frequency is much higher and the radius is smaller in the ultrasonic elliptical vibration cutting. These differences enable the mirror surface machining with diamond tools. Unlike the end milling process, the feed speed is identical with the cutting speed in the proposed method. Although the cutting speed in the elliptical vibration cutting is not high as mentioned above, it is not low or rather high as the feed speed in sculpturing processes.

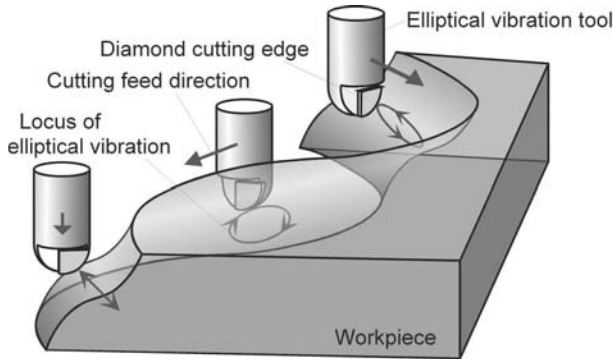
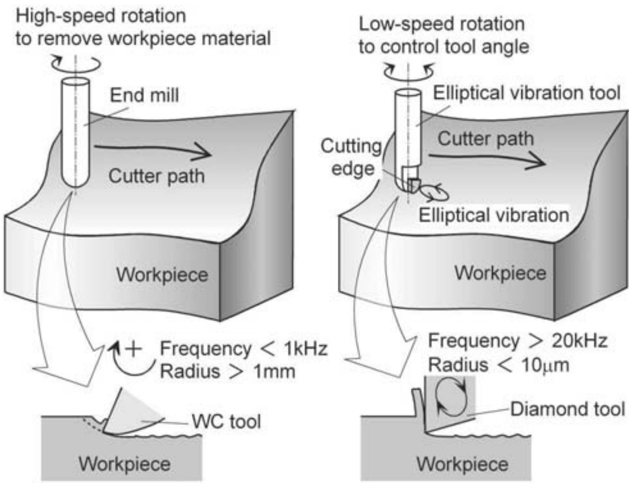


Fig.1 Elliptical vibration cutting for three-dimensional free surface



(a) Ball end milling process (b) Proposed method

Fig.2 Comparison between end milling and proposed machining for sculptured surfaces

Consequently, machining efficiency can be relatively higher with higher cutting feed speed and with smaller theoretical roughness as compared with the end milling technology[8].

In the proposed machining, a slender tool like an end mill needs to be vibrated elliptically at an ultrasonic frequency in an inclined plane as shown in the figure. Additionally the ultrasonic elliptical vibration locus has to be kept to a constant ultra-precisely in the inclined plane while cutting in order to guarantee machining accuracy. Note that amplitude variation in the depth of cut direction can cause variation of the depth of cut, which results in machining accuracy deterioration.

In order to attain the desirable vibration, a three-degree-of-freedom (3-DOF) ultrasonic vibrator shown in Fig. 3 was developed. The vibrator can be actuated by some attached PZT actuators. Since the vibrator is designed to have same resonant frequencies in the longitudinal and bending modes, it can generate large longitudinal and bending vibrations simultaneously at the same ultrasonic frequency of about 34.4 kHz by exciting the actuators. The vibration can also be detected in real time by attached PZT sensors. The vibration in each vibration mode is controlled with a feedback control system[9]. Thus, an arbitrary 3-DOF elliptical vibration can be obtained at the diamond tool tip mounted on the insert tool shank by combining both resonant vibration modes with some phase shift. Figure 4 shows examples of measured vibrations. A similar 2-DOF vibration system, which can generate similar ultrasonic elliptical vibration in appropriate direction, was also developed. The configurations of the 2-DOF system are

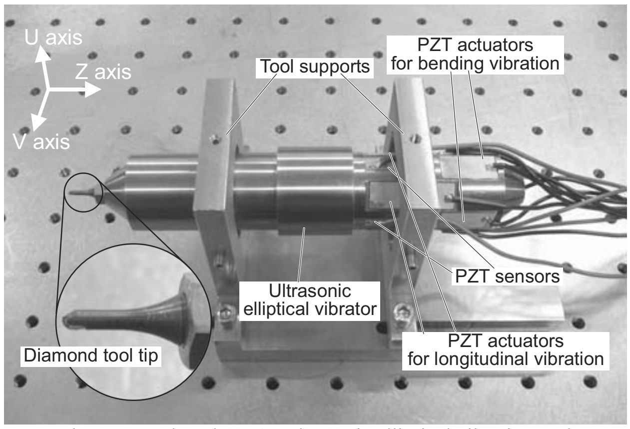
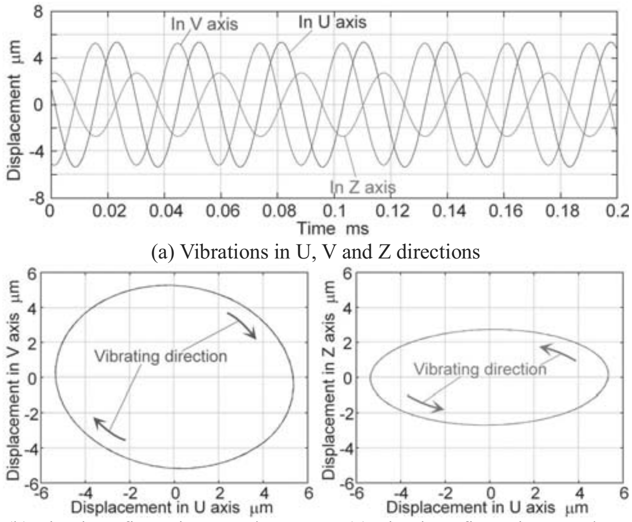


Fig.3 Developed 3 DOF ultrasonic elliptical vibration tool



(a) Vibrations in U, V and Z directions

(b) Lissajous figure in U-V plane (c) Lissajous figure in U-Z plane

Fig.4 Measured elliptical vibration

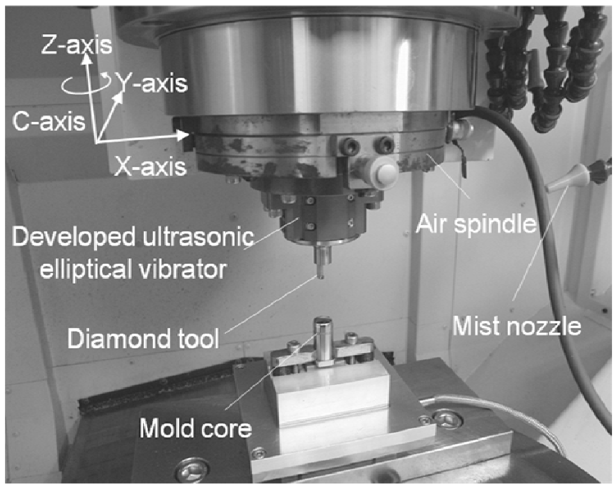


Fig.5 Experimental setup for sculpturing applications

simpler as compared with the 3-DOF system, and thus it is easy to control in practice.

Feasibility of mirror surface sculpturing for practical applications was experimentally verified. A precision machine tool, which was developed based on a commercial machining center (MU-400VA-DD: OKUMA Corporation), was utilized[10]. Figure 5 shows a setup for sculpturing experiments. The developed vibration tool is attached to a C-axis air spindle, and it is connected to the control system by a

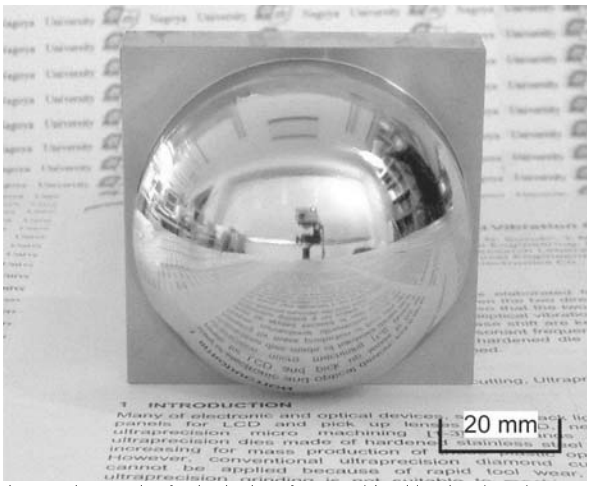
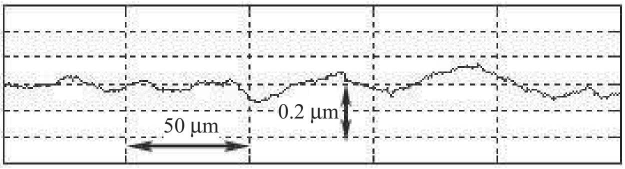
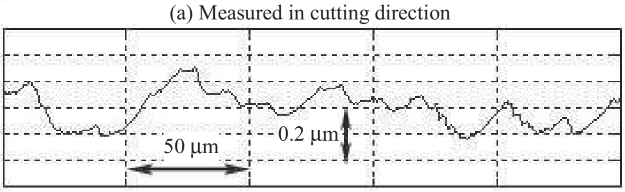


Fig.6 Photgraph of spherical surface machined by developed system [Cutting conditions] Feed rate: 15 μm/rev, Depth of cut: about 3 μm, Cutting speed: 0-1.27 m/min, Cutting fluid: oil mist, [Tool] Material: single crystal diamond, Rake angle: 0 deg, Clearance angle: 15 deg, Nose radius: 1 mm, [Workpiece] Material: die steel (JIS: NAK80), Hardness: HRC40, [Vibration conditions] Vibration amplitude: 6-6-3 $\mu m_{p\text{-}p}$, Frequency: 34.4 kHz, Phase: 90-90 deg



(a) Measured in cutting direction



(b) Measured in feed direction

Fig.7 Surface profiles of spherical workpiece

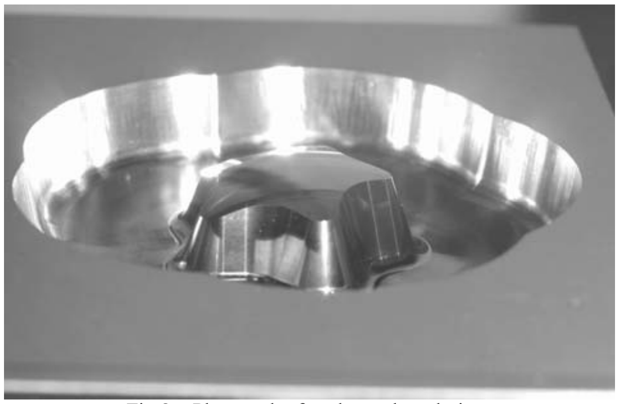


Fig.8 Photgraph of sculptured workpiece

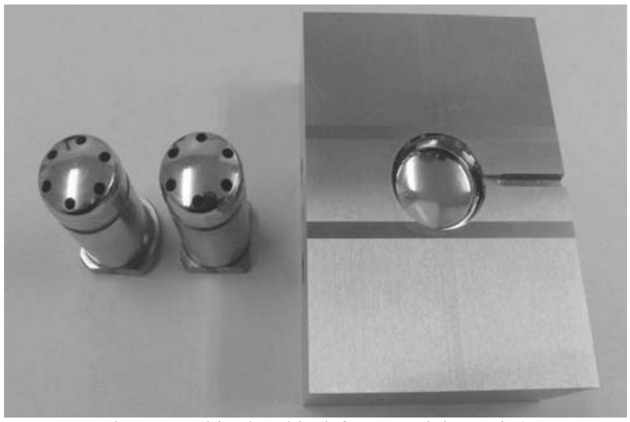


Fig.9 Machined molds (left: cores, right: cavity) [Cutting conditions] Feed rate: 20 μm/rev, Depth of cut: 5 μm, Cutting speed: less than 0.64 m/min, Cutting fluid: oil mist, [Tool] Material: single crystal diamond, Rake angle: 0 deg, Clearance angle: 10 deg, Nose radius: 1 mm, [Workpiece] Material: die steel (JIS: SUS420J2), Hardness: HRC54, [Vibration conditions] Vibration amplitude: 4 $\mu m_{p\text{-}p}$ (circular), Frequency: 38 kHz

bunch of electric wires, thus the C axis cannot be rotated infinitely. The tool is fed along the sculptured surface at each Z level and rotated in accordance with the cut surface orientation in the proposed sculpturing method, as shown in Fig. 1. Therefore, the C axis needs to be counter-rotated to rewind the wires after each rotation. Workpieces were machined precisely by the ball end milling before the cutting tests in advance.

Figure 6 shows a photograph of the spherical steel mirror finished with the 3-DOF elliptical vibration system. The result indicates that simple curved mirror surfaces of hardened die steel can be obtained by the proposed elliptical vibration cutting with the 4 axis control. Figure 7 shows surface profiles measured by the surface profiler (ET4000: Kosaka Laboratory Ltd.) at the position where the normal vector makes 30 deg with that at the top of the sphere. The maximum roughness of about 280 nm Rz is achieved for the spherical surface, as shown in the figure.

Subsequently, sculpturing test of more complicated geometry of hardened steel workpiece was conducted by using the 2-DOF elliptical vibration system. The photograph of machined workpiece is shown in Fig. 8. As shown in the figure, mirror quality surface can be obtained successfully. Measured surface roughness of the spherical center part was less than 100 nm Rz. Surface quality of other parts seems to be as fine as that of the spherical center part, though it is difficult to measure the surface roughness.

The mold cores were machined with same 2-DOF vibration control system. Total machining time for the mold cores and cavity were 110 min and 120 min. Mirror quality surfaces were obtained successfully by applying the developed vibration system, as shown in Fig. 9. Almost all surfaces were consequently machined without any surface quality deteriorations. Maximum surface roughness was 124 nm Rz. The quality seems to be remarkably fine considering the motion accuracy of the machine tool used in the experiment. However the self-excited chatter vibration occurred while machining steep surfaces, which are almost parallel to the axial direction, even at a small depth of cut of 5 μm. Since the chatter vibration can cause surface deterioration and critical damage on the cutting edge, it needs to be suppressed in practice. Now, this chatter generation mechanism is under investigation as well as chatter stability analysis and suppression methods.

3. Nano-scale sculpturing by applying elliptical vibration cutting

In order to apply elliptical vibration cutting technology to ultraprecision cutting applications similarly to the conventional diamond cutting, it is important to keep the elliptical vibration locus ultra-precisely constant. Otherwise, the depth of cut varies and ultra-precision cutting cannot be achieved in practice. On the other hand, this fact means at the same time that the depth of cut can be actively controlled by controlling the vibration amplitude in the depth of cut direction while machining. By utilizing this function to serve as a sort of fast tool servo (FTS), the ultra-precision sculpturing of difficult-to-cut materials in micro/nano scale is achieved efficiently.

Figure 10 shows the proposed machining with depth of cut control in elliptical vibration cutting. The vibration amplitude in the depth of cut direction is controlled simultaneously in the proposed machining process. The trajectory of the cutting edge, then, changes dynamically, and its envelope is transferred to the finished surface. By controlling the amplitude ultra-precisely at high speed, the ultra-precision sculpturing of the difficult-to-cut materials can be achieved efficiently without using conventional FTS technology[11]. In other words, the elliptical vibration cutting technology is equipped with a FTS function by itself. And thus, it is redundant and even disadvantageous to combine the elliptical vibration tool with the conventional FTS, since both devices have actuators and the vibration tool is too heavy to be actuated at high frequency by the FTS.

Although amplitude control command is not completely identical with the envelope of the cutting edge trajectory, as shown in Fig. 10, this difference is insignificant in practice when the slope is not steep. The depth of cut can be controlled within half of the maximum amplitude in the depth of cut direction, and available frequency range of the amplitude control is limited to that which is relatively lower than the elliptical vibration frequency. Therefore, performance in the role as FTS strongly depends on the specifications of the vibrator.

Figure 11 shows the developed system of the high-speed amplitude control of elliptical vibration at a frequency of about 36 kHz. A 2-DOF elliptical vibration tool[12], which was designed to generate arbitrary elliptical vibration, is utilized. The vibrator is actuated by using some PZT actuators, which are sandwiched with metal cylindrical parts, namely a bolt clamped Langevin type transducer (BLT). As the vibrator is designed to have same resonant frequencies in second resonant mode of longitudinal vibration and fifth resonant mode of bending vibration, it can generate large longitudinal and bending vibrations simultaneously at the same ultrasonic frequency by applying exciting voltages to the actuators. Thus, an arbitrary 2-DOF elliptical vibration can be obtained at the diamond tool tip attached to the vibrator by combining both resonant vibration modes with some phase shift. Longitudinal vibration direction corresponds to depth of cut direction in the present study.

Gain of the amplifier can be controlled by external input in the developed system, and thus the exciting voltage supplied to the actuator is changed. The amplitude is, consequently, controlled by the external input. As the maximum amplitude in the depth of cut direction is 4 $\mu m_{p\text{-}p}$, the vibration amplitude can be controlled to change the depth of cut within 2 μm by this system. Measured frequency response of amplitude control is shown in Fig. 12. It is possible to control the vibration amplitude with a frequency bandwidth of more than 300 Hz. This frequency bandwidth is relatively narrow as compared with that of conventional FTS. It might not, however, be a crucial problem because the elliptical vibration cutting technology is available only at relatively low cutting speed. And this low cutting speed is also not disadvantage in sculpturing as mentioned in chapter 2.

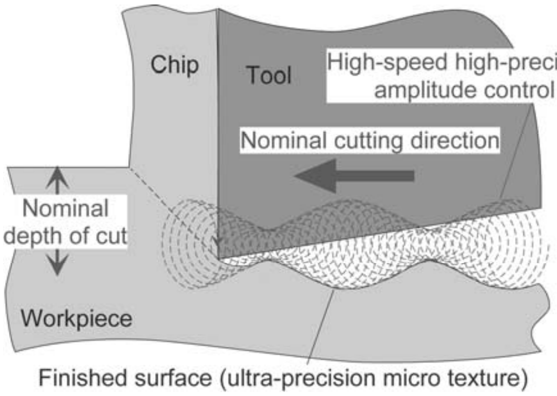


Fig.10 Machining by controlling amplitude in elliptical vibration cutting

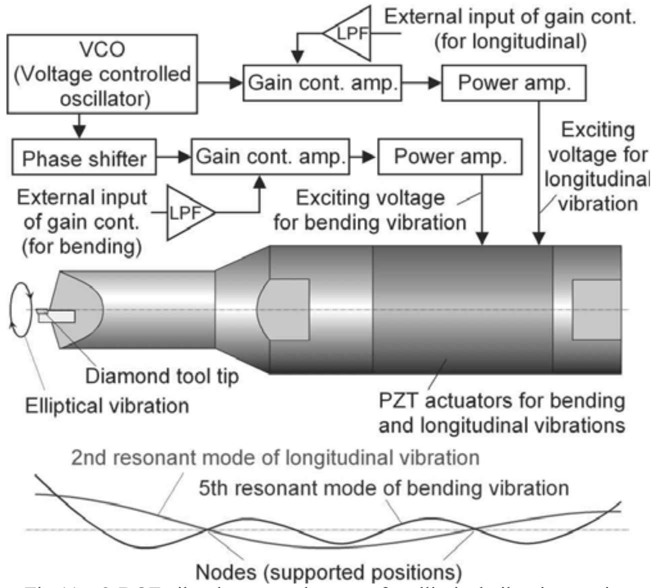


Fig.11 2-DOF vibration control system for elliptical vibration cutting

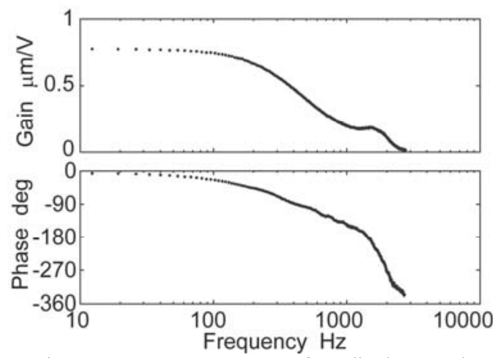


Fig. 12 Frequency response of amplitude control

The developed control system was applied to grooving experiments. Figure 13 shows an experimental setup. The ultrasonic elliptical vibration tool is mounted on an ultra-precision planing machine, NIC-300 (Nagase Integrex Co., Ltd.), which consists of three feed tables with double hydrostatic oil guideways in XYZ axes, two rotary index tables in BC axes and a five-axis control system. The vibration tool was fed in the X-axis direction. The vibration amplitude was controlled with various wave commands such as sinusoidal, ramp and zigzag waves, at the same time, and then, micro textured grooves were formed on the surface of a hardened steel workpiece. The vibration amplitude was controlled to change from 2 $\mu m_{p\text{-}p}$ to 4 $\mu m_{p\text{-}p}$ in the commands. This corresponds to the depth of cut variation of 1

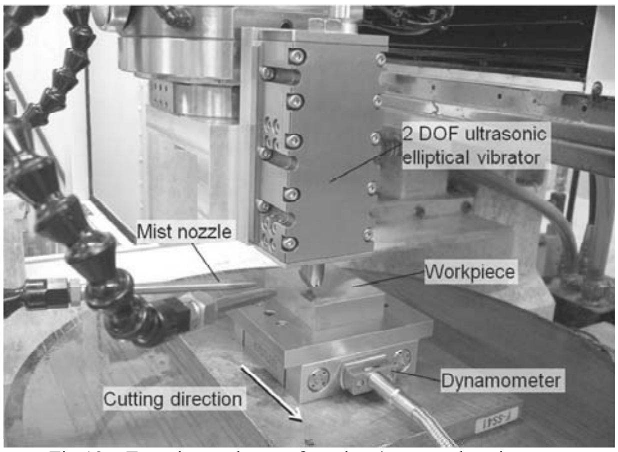


Fig.13 Experimental setup for micro/nano sculpturing tests

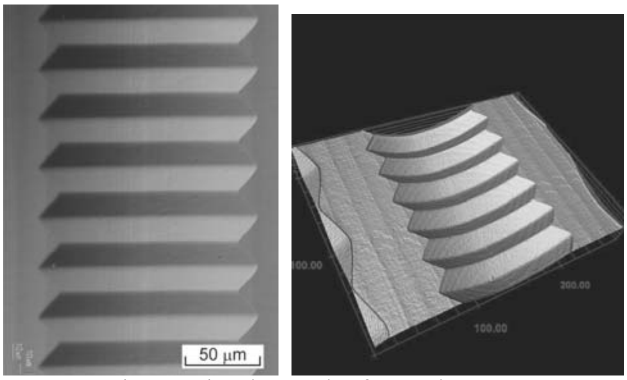


Fig.14 Microphotographs of textured grooves
[Cutting conditions] Maximum depth of cut: 2.5 μm, Cutting speed: less than 0.2 m/min, [Tool] Material: single crystal diamond, Rake angle: 0 deg, Clearance angle: 10 deg, Nose radius: 1 mm, [Workpiece] Material: die steel (JIS: SUS420J2), Hardness: HRC53, [Vibration conditions] Vibration amplitude: 4 $\mu m_{p\text{-}p}$ (circular), Frequency: 38 kHz, Command wave: zigzag, Command frequency: 100 Hz

μm. On the other hand, the amplitude in the cutting direction is set to be constant, 4 $\mu m_{p\text{-}p}$.

Figures 14 shows microphotographs of a groove machined at the cutting speed of 0.2 m/min by the single crystal diamond tool with a nose radius of 1 mm. It is obviously confirmed that the groove with ultra-precision micro texture can be machined successfully on the hardened steel, and mirror surface quality can be obtained. Surface profiles of the grooves were measured, and it was also confirmed that measured surface profiles roughly agreed with the command waves. However, steep corners of zigzag grooves are rounded, and thus, the step heights are relatively smaller than the variation range of command waves of 1 μm due to less frequency response.

In order to attain arbitrary sculpturing, an ultra-precision micro/nano sculpturing system was developed by using the developed vibration control system and the ultra-precision planing machine. Figure 15 shows the developed sculpturing system, where the planing machine is simply controlled to machine a plane surface at constant cutting speed. The ultrasonic elliptical vibration tool is attached on the Z-axis table of the machine tool. The vibration amplitude in the depth of cut direction along the Z-axis is controlled in synchronization with cutting feed motion in the X-axis, and then, arbitrary micro/nano sculpturing can be attained on a flat top surface of a steel workpiece.

The X-axis coordinate value is constantly monitored in the developed system by directly communicating with NC control system

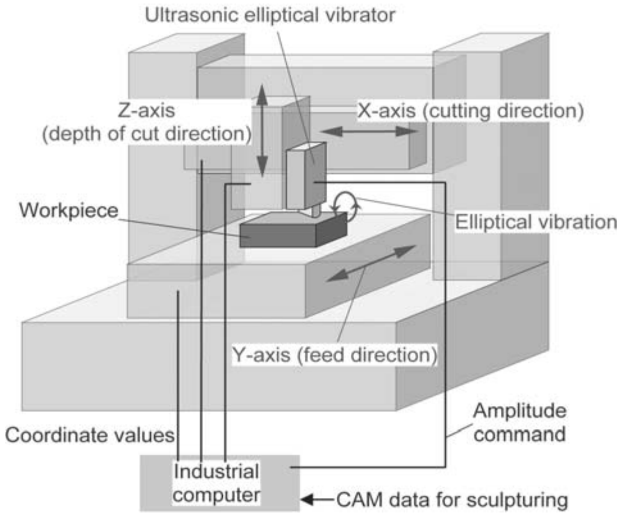


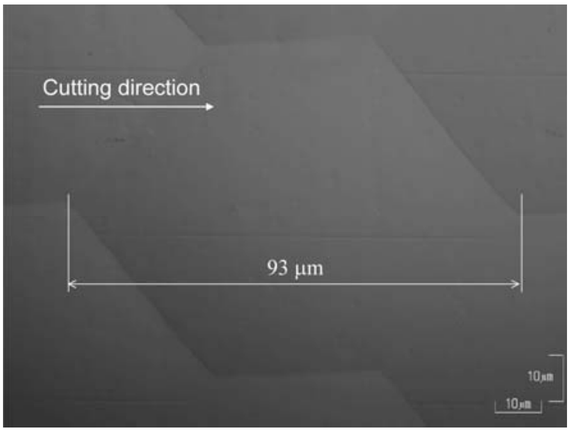
Fig.15 Micro/nano sculpturing system using elliptical vibration cutting

Fig.16 Photographs of sculptured letters (overview and close up)
[Cutting conditions] Pick feed: 20 μm, Depth of cut: 20 μm, Cutting speed: 1 m/min, Cutting fluid: oil mist, [Tool] Material: single crystal diamond, Rake angle: 0 deg, Clearance angle: 10 deg, Nose radius: 1 mm, [Workpiece] Material: die steel (JIS: SUS420J2), Hardness: HRC53, [Vibration conditions] Vibration amplitude: 2-4 $\mu m_{p\text{-}p}$, Frequency: 36 kHz

or by using an external optical sensor. In every cutting feed, an X-axis coordinate is detected after the feed speed becomes constant but before the cutting starts. The dynamic command signal for vibration amplitude control is subsequently input to the elliptical vibration control system based on the detected X-axis coordinate, the cutting speed, and the amplitude command table, which is calculated from CAD data of objects. Thus, the amplitude is controlled to change the depth of cut in accordance with the CAD data in real time. Consequently, sophisticated structures can be machined on the steel materials efficiently by merely combining simple planing operations at constant cutting speed with high-speed depth of cut control. An industrial computer is utilized to detect the X-axis coordinate and to generate the voltage signal for controlling vibration amplitude.

The developed machining system was applied to sculpturing experiments of picture images. CAD data for sculpturing were produced from letter image. As the vibration amplitude was changed within a range from 2 $\mu m_{p\text{-}p}$ to 4 $\mu m_{p\text{-}p}$, the depth of cut was changed within 1 µm. Hardened steel workpieces (64x48 mm) were machined with a diamond tool, whose nose radius is 1 mm. The size of original images is set to 3200x2400 pixels, and thus, 1 pixel corresponds to 20x20 µm. Figure 16 shows photographs of letters sculptured on the hardened steel. The whole surface is machined in about 260 minutes with the developed sculpturing system. All letters were machined to be concave with a depth of 1 µm. As shown in the figure, the letters are sculptured successfully. It was confirmed that the measured step height of sculptured letters agreed with the desired depth of 1 µm. Any unusual tool damages were not observed after the experiment.

Nano sculpturing experiments involving various dimple patterns were also carried out with the developed sculpturing system. Sinusoidal commands to control the vibration amplitude were input to the elliptical vibration control system during machining, and the phase of the sinusoidal commands was changed by 180 deg in every cutting feed, so that precisely aligned patterns were sculptured. Figure 17 shows a microphotograph and a profile of sculptured dimples. The hexagonal dimple patterns, whose borders are sharp, can be observed. It was also confirmed that the measured dimple depth of 0.78 µm corresponds well with an expected dimple depth of 0.75 µm, which is calculated theoretically from the vibration conditions, the cutting conditions and the tool geometry. The experimental results show that a variety of dimple patterns are obtained directly on the steel materials by using the developed sculpturing system.



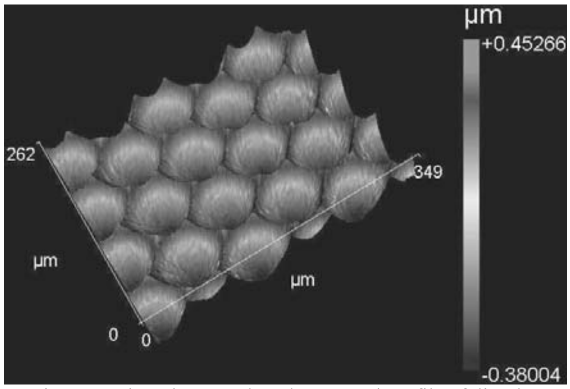


Fig.17 Microphotograph and measured profile of dimples [Cutting conditions] Pick feed: 34 µm, Maximum depth of cut: 10 µm, Cutting speed: 0.8 m/min, Cutting fluid: oil mist, [Tool] Material: single crystal diamond, Rake angle: 0 deg, Clearance angle: 10 deg, Nose radius: 1 mm, [Workpiece] Material: die steel (JIS: SUS420J2), Hardness: HRC53, [Vibration conditions] Vibration amplitude: about 2-4 $\mu m_{p\text{-}p}$, Frequency: 36.7 kHz, Command wave: sinusoidal, Command frequency: 100 Hz

4. Conclusion

Novel micro- and macro-scale sculpturing methods by applying elliptical vibration cutting were presented. They are not only applicable to mirror surface sculpturing of steel materials but also high-performance in cutting efficiency. Practical machining systems including sophisticated ultrasonic vibration system were developed. Experimental investigations indicated that practical macro-scale mirror surface sculpturing of molds and micro/nano-scale ultraprecision sculpturing on plane surfaces can be attained. And thus, feasibility of proposed sculpturing was verified. Now, more challenging machining method combining both scale sculpturing is under investigation.

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