Ultraprecision Micromachining of Hardened Steel by Applying Ultrasonic Elliptical Vibration Cutting

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Abstract:
Ultraprecision micromachining of hardened steel with a single point diamond tool, which is practically impossible due to rapid tool wear, is realized by applying 'Elliptical Vibration Cutting' technology, which has been developed by the authors. A practical ultrasonic elliptical vibration cutting system is developed in the present research, which consists of a practical vibration control system and an ultraprecision planing machine. The control system is fabricated to keep the elliptical vibration to have a desired locus, where the amplitudes of the two directional vibrations and their phase shift are kept to be desired values, and the vibration frequency is locked to an average value of their resonant frequencies. The vibration control system is mounted on the ultraprecision planing machine, 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 developed elliptical vibration cutting system is applied to ultraprecision diamond planing of hardened die steel, and a high quality mirror surface is obtained over a large area of the whole finished surface. Maximum roughness of the finished surface is less than 0.04 μm Ry, although the cutting distance reaches 1110 m. On the other hand, the surface finished by ordinary cutting without the vibration, is cloudy with maximum roughness of more than 0.52 μm Ry within a cutting distance of 1 m. Based on this advantage, the elliptical vibration cutting system is successfully applied to ultraprecision micromachining of dies for a front light panel of LCD. An optical quality surface with fine microgrooves over a large area of 122 x 91 mm^2 and with surface roughness of less than 0.04 μm Ry is obtained by the developed system, which is difficult for any conventional machining methods including grinding, polishing and ordinary cutting.

1. Introduction

Many of electronic and optical parts used for information communication equipment and devices, such as front and back light panels for LCD, glass substrates with barrier ribs for PDP, holographic optical elements and optical wave-guides, need ultraprecision micromachining [1,2]. The demands for ultraprecision dies made of hardened stainless steel are increasing for mass production of those devices. Machining, i.e. cutting and grinding, and chemical etching have been applied to micromachining. However, conventional ultraprecision diamond cutting can not be applied to machining of die steel due to rapid tool wear [3-5], while ultraprecision grinding and chemical etching are not suitable to machine such ultraprecision micro structures especially with sharp edges. Thus, the ultraprecision micromachining of die steel can not be realized by the conventional methods.

The authors have developed a new cutting method named elliptical vibration cutting and clarified that ultraprecision diamond cutting of hardened steel can be realized by applying this method [6-12].

In order to realize ultraprecision micromachining over a relatively large area, a new ultraprecision elliptical vibration cutting system is developed in the present research, which consists of a practical type of elliptical vibration control system and an ultraprecision planing machine with long strokes. The vibration control system is fabricated to stabilize the elliptical vibration against the cutting load and the temperature change, where the vibration amplitudes and their

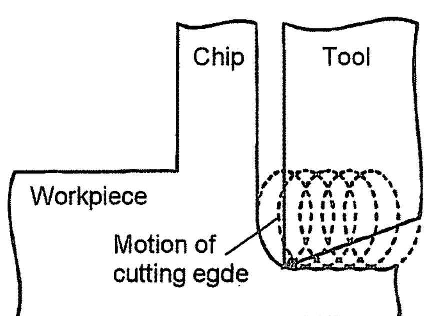

Figure 1: Elliptical vibration cutting process.

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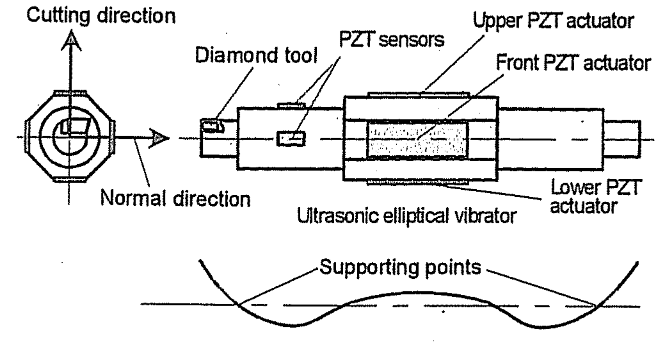


Figure 2: Ultrasonic elliptical vibrator and its resonant mode.

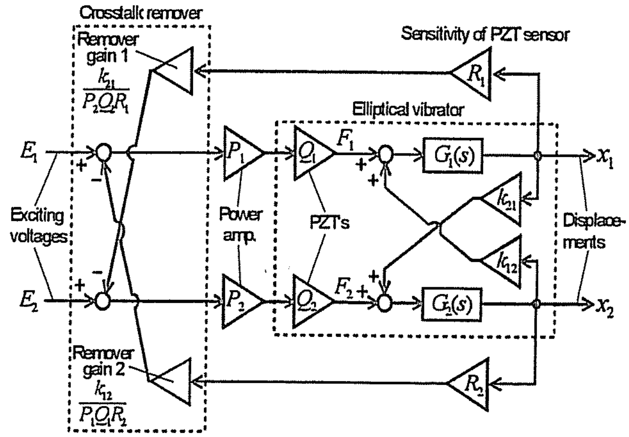


Figure 3: Method to remove cross talks.
Subscripts 1 and 2 indicate cutting and normal directions respectively.

phase shift are kept to be desired values. The resonant frequency is also chased automatically by the control system. The vibration control system is mounted on an ultraprecision planing machine, 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 XY feed tables have a relatively long stroke of 400 mm to machine large surfaces.

By utilizing the developed elliptical vibration cutting system, performance of the elliptical vibration cutting was examined by machining a large flat surface of hardened die steel with an area of 122 x 91 mm^2. Then, the system was further applied to ultraprecision micromachining of hardened dies for a front light panel of LCD and its practical validity is verified experimentally in the present research.

2. Elliptical Vibration Cutting Process

Figure 1 shows a schematic illustration of elliptical vibration cutting process. The tool is vibrated elliptically and fed in the nominal cutting direction relatively to the workpiece at the same time, 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 reversed, the shear angle is increased and consequently the cutting force and the cutting energy are reduced significantly.

It should be noted that deviation of the elliptical vibration locus, especially the vibration amplitude in the thrust direction, causes errors in the workpiece profile. It is, therefore, necessary to control the vibration locus precisely during machining.

3. Ultrasonic Ellipticalvibration Cutting System

3.1 Ultrasonic Elliptical Vibration System

Figure 2 shows a schematic illustration of the ultrasonic elliptical vibrator, whose resonant frequency is 20 kHz. The vibrator has 4 large piezoelectric plates as actuators and 2 small plates as sensors. It is vibrated in the cutting direction in the third resonant mode by applying sinusoidal voltage to the upper and lower actuators with a phase shift of 180 degrees. It is also vibrated in the normal direction to the cutting direction and the vibrator axis by exciting the front and back actuators. The diamond tool tip is set at the end of the vibrator and vibrated elliptically by resonating the vibrator in the both directions with some phase shift. The two directional vibrations are detected by the two sensors respectively.

It is important for the vibration control that the two directional vibrations are independent of each other. However, the two vibrations interfere considerably in practice, i.e. the vibrator vibrates in an undesirable direction even though it is forced to vibrate only in another direction. The undesirable vibration is due to cross talk. Assuming that the cross talk is caused by the cross stiffness k_{12} and k_{21} shown in Figure 3, the cross talks are removed as follows. The vibration signals detected by the piezoelectric sensors are input to the cross talk remover as feedback signals, and the exciting voltages are compensated by the remover so as to cancel the cross stiffness k_{12} and k_{21}. Then, the compensated voltages are applied to the piezoelectric actuators via the power amplifiers. It has been confirmed that the crosstalk can be removed almost completely by this method [11].

A new practical type of vibration control system is developed here by utilizing the above mentioned cross talk remover, which is shown in Figures 4 and 5. The vibration amplitudes and their phase shift are kept to be desired values by the system. The resonant frequencies are slightly different in the two directions even after adjustment, and they change due to cutting force and temperature change. Thus, their average resonant frequency is chased automatically by the control system.

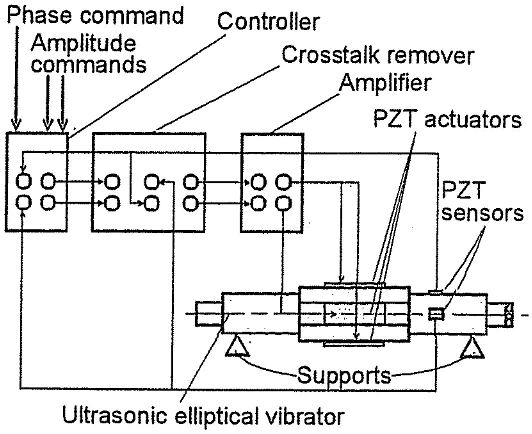


Figure 4: Vibration control system.

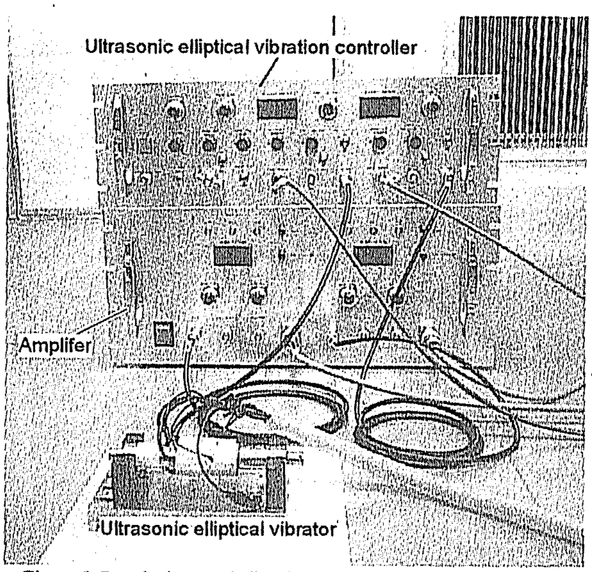


Figure 5: Practical type of vibration control system developed here.

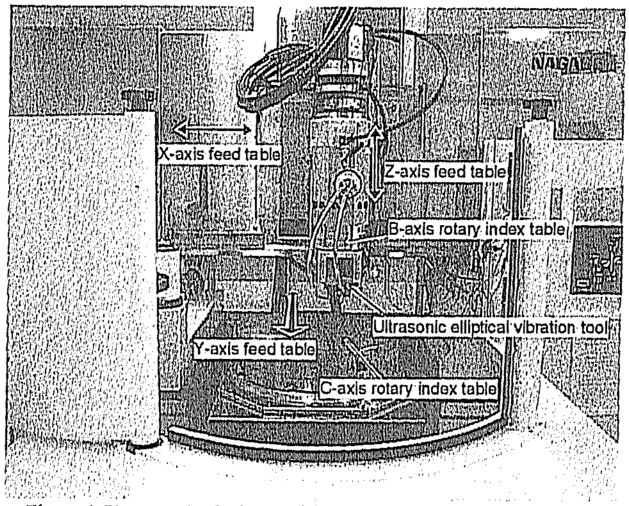


Figure 6: Photograph of Ultraprecision planing machine equipped with ultrasonic elliptical vibration tool.

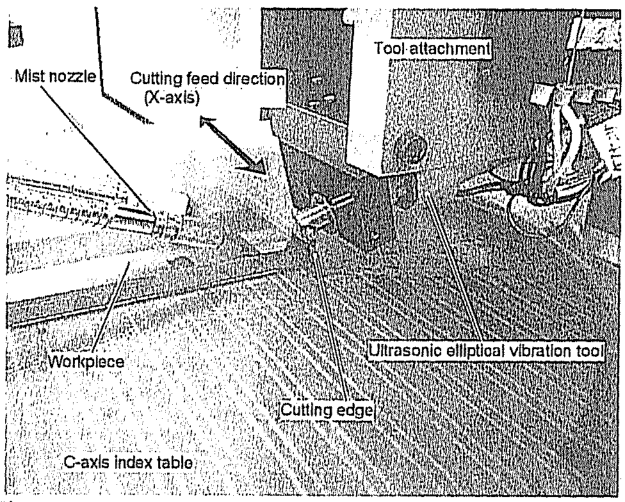


Figure 7: Setup for ultraprecision planing experiment with ultrasonic elliptical vibration cutting system.

3.2 Elliptical Vibration Cutting Machine

The developed vibration control system is mounted as shown in Figure 6 on an ultraprecision planing machine, NIC-300 made by 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 X and Y axes have a long feed stroke of 400 mm, so that a large surface up to 400 x 400 mm^2 can be finished by the present machining system.

Figure 7 shows a set up for the ultraprecision elliptical vibration planing experiments, where the X axis is utilized for cutting feed. The elliptical vibration tool is attached to the upper index table and the workpiece is fixed to the lower index table of the ultraprecision planing machine.

4. ULTRAPRECISION MICROMACHINING OF HARDENED DIE STEEL

4.1 Ultraprecision Planing of Hardened Steel

The ultraprecision diamond cutting experiments were carried out with the developed elliptical vibration cutting system.

For comparison, the ordinary cutting without vibration was applied first to planing of hardened steel, JIS: SUS420J2, with hardness of HRC42. The cutting speed was set to 1 m/min, the feed, 5 μm, and the depth of cut, 3.5 μm, as summarized in Table 1.

Figure 8 shows the surface finished by the ordinary cutting. Figure 9(a) shows the surface profile measured in the

Table 1: Experimental conditions in machining of hardened die steel.

Cutting method		Ordinary cutting	Elliptical vibration cutting	
Cut shape		Flat surface		Microgrooves
Vibration conditions	Frequency (kHz)	-	19.6	
	Amplitude (μm_{p-p})	-	6	3
	Locus of vibration	-	Circle	
Cutting conditions	Cutting speed (m/min)	1	0.7	0.25
	Depth of cut (μm)	3.5	5	1
	Feed (μm)	5	10	300
Tool	Edge shape	R, Radius: 1 mm		V, Angle: 107°
	Rake angle (deg.)	0		
Workpiece	Material	JIS: SUS420J2		
	Hardness (HRC)	42	53	
	Shape (mm)	Cylindrical block φ6-27	Rectangular plate 122×91	

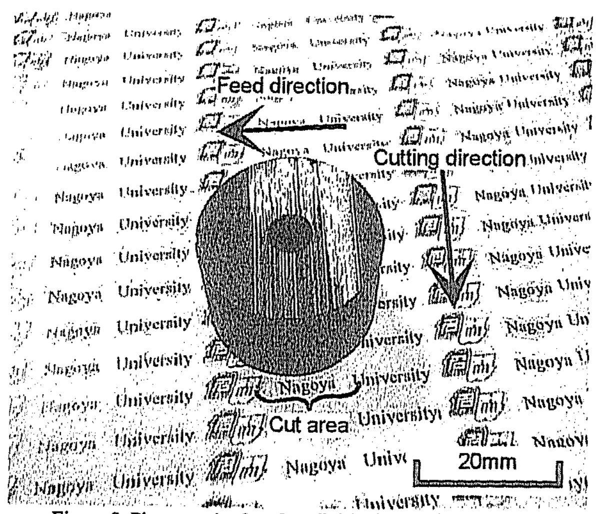
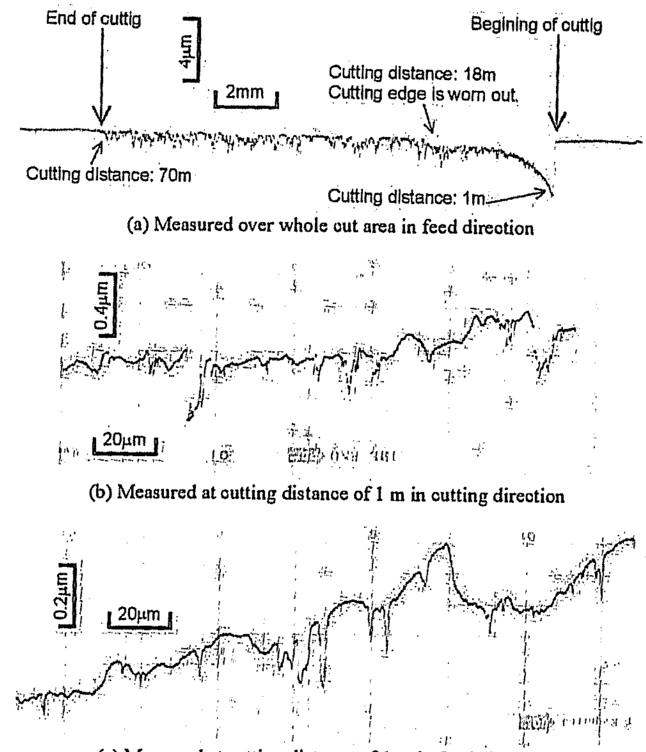


Figure 8: Photograph of surface finished by ordinary cutting.

feed direction, which indicates that the diamond cutting edge was worn out after cutting of 18 m though the total cutting distance was 70 m, i.e. the workpiece material was removed only at the beginning and rubbed during the rest of cutting period. Figures 9(b) and (c) show the surface roughness at a cutting distance of 1 m, where (b) shows the roughness measured in the cutting direction, and (c) in the feed direction. They show that the roughness is more than 0.52 μm Ry even at the beginning of cutting. It is confirmed that the hardened die steel can not be finished by the ordinary diamond cutting in practice due to the excessive tool wear [3-5]. SEM photographs of the cutting edge before and after the cutting experiment are shown in Figure 10. The cutting edge was worn out completely by 3.5 μm, which corresponds to the depth of cut.

The developed elliptical vibration cutting system was applied to ultraprecision planing of a relatively large flat surface of hardened die steel, whose hardness was HRC53. The cutting speed was set to 0.7 m/min, the feed, 10 μm, and the depth of cut, 5 μm in this experiment, as shown in Table 1.

An optical quality mirror surface finish was realized over the whole area of the large finished surface with the developed elliptical vibration cutting system, as shown in Figure 11. The measured surface roughness is less than 0.04 μm Ry even at a cutting distance of 1065 m, as shown in Figure 12. The optical quality surface was obtained up to the long cutting distance, even though the diamond cutting edge was worn to some extent as shown in Figure 13. The

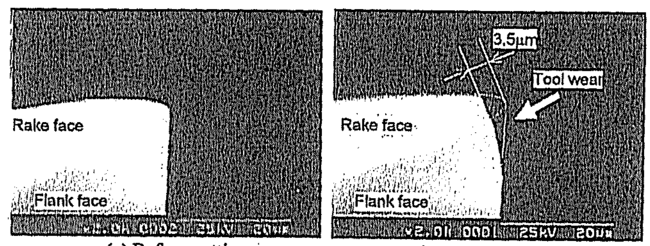


(a) Measured over whole cut area in feed direction

(b) Measured at cutting distance of 1 m in cutting direction

(c) Measured at cutting distance of 1 m in feed direction

Figure 9: Profiles of surface finished by ordinary cutting.



(a) Before cutting (b) After cutting

Figure 10: SEM Photographs of cutting edge before and after ordinary cutting experiment.

chippings observed in the photograph occurred in another experiment, and they are not related with the present cutting experiment. It is clarified that the tool wear is restrained drastically by the present system, and that the diamond cutting edge can be used over the long cutting distance of 1110 m, which corresponds to the large area of 122 x 91 mm^2 in this case. The practical ultraprecision machining of large area of hardened steel with a single point diamond tool, which is practically impossible for the ordinary cutting, can be realized by applying the developed ultrasonic elliptical vibration cutting system.

4.2 Ultraprecision Microgooving of Hardened Steel

Based on the above advantage, ultraprecision micromachining of hardened dies for a front light panel of LCD was conducted here with the developed elliptical vibration cutting system. The machining conditions are summarized in Table 1.

Figure 14 shows the finished mirror surface with fine microgrooves. It is made of hardened die steel, whose hardness is HRC53. Figure 15 shows a microphotograph of the microgooves formed over the large workpiece surface. Figure 16 shows the profiles of the finished surface measured in the feed direction and in the cutting direction. As shown in the figures, the surface roughness is less than 0.04 μm Ry, and the ultraprecision microgooving of hardened die steel was successfully realized by the developed ultrasonic elliptical vibration cutting system.

It is verified experimentally that the developed system can be applied to ultraprecision micro cutting of large area of hardened die steel, which is impossible in practice for the conventional machining methods.

5. CONCLUSIONS

A new machining system is developed by employing the elliptical vibration cutting technology, and it is applied to ultraprecision planing and microgrooving of hardened die steel with the relatively large surface area. The results obtained in the present research can be summarized as follows.

(1) The new machining system is developed by fabricating the practical type of elliptical vibration control system and combining it with the ultraprecision planing machine with long strokes.

(2) The optical quality mirror surface of the hardened die steel with maximum roughness of less than 0.04 μm Ry was successfully obtained over the large area of 122 x 91 mm^2 by applying the developed elliptical vibration cutting system.

(3) Ultraprecision microgrooving of hardened die steel, i.e. machining of the die for a front light panel of LCD, was achieved with maximum roughness of less than 0.04 μm Ry with the developed system.

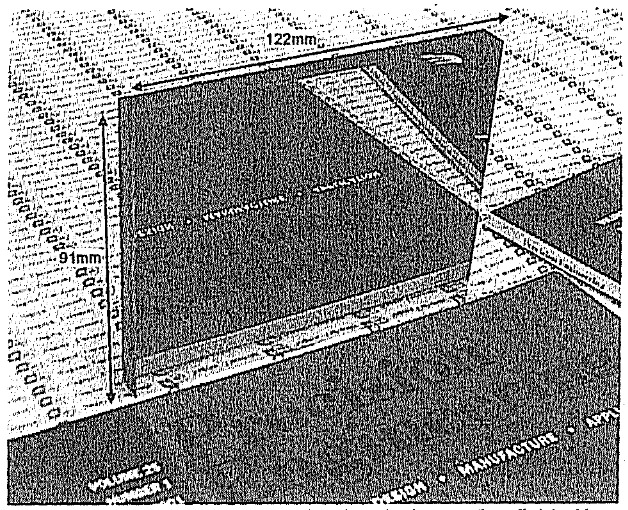
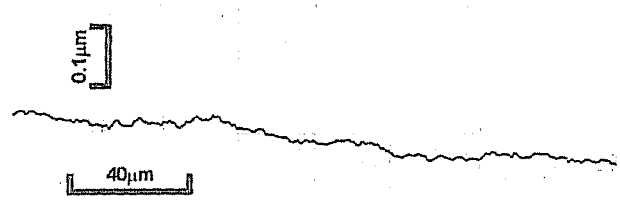
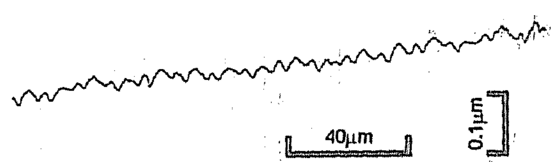


Figure 11: Photograph of large hardened steel mirror surface finished by developed elliptical vibration cutting system.



(a) Measured in cutting direction



(b) Measured in feed direction

Figure 12: Profiles of surface finished by elliptical vibration cutting, measured at cutting distance of 1065 m.

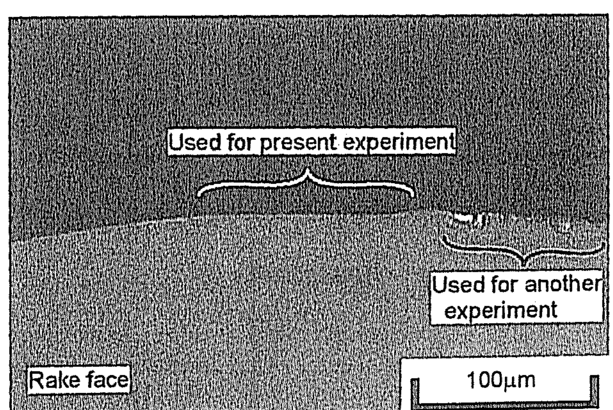


Figure 13: Microphotograph of cutting edge after elliptical vibration cutting of 1110 m.

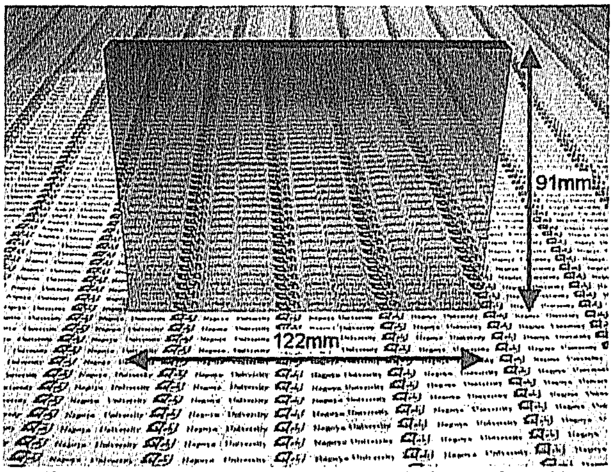


Figure 14: Photograph of large hardened steel mirror surface with microgooves, machined as die for front light panel of LCD.

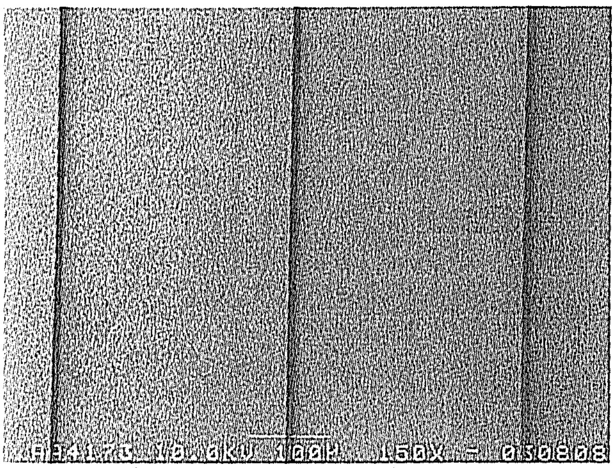


Figure 15: SEM photograph of microgrooves.

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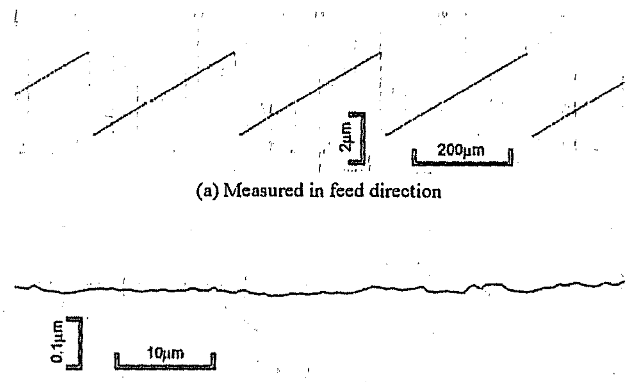

(a) Measured in feed direction

(b) Measured in cutting direction

Figure 16: Profiles of surface grooved by the developed elliptical vibration cutting system.

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