Ultrasonically Assisted Grinding for Mirror Surface Finishing of Dies with Electroplated Diamond Tools

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This paper describes ultrasonically assisted grinding used to obtain a glossy surface quickly and precisely. High-quality surfaces are required for plastic injection molding dies used in the production of plastic parts such as dials for cellular phones. Traditionally, in order to finish the dies, manual polishing by a skilled worker has been required after the machining processes, such as electro discharge machining (EDM), which leaves an affected layer, and milling, which leaves tooling marks. However, manual polishing causes detrimental geometrical deviations of the die and consumes several days to finish a die surface. Therefore, a machining process for finishing dies without manual polishing to improve the surface roughness and form accuracy would be extremely valuable. In this study, a 3D positioning machine equipped with an ultrasonic spindle was used to conduct grinding experiments. An electroplated diamond tool was used for these experiments. Generally, diamond tools cannot grind steel because of excessive wear as a result of carbon atoms diffusing into bulk steel and chips. However, ultrasonically assisted grinding can achieve a fine surface (roughness Rz of 0.4 μm) on die steel without severe tool wear. The final aim of this study is to realize mirror surface grinding for injection molding dies without manual polishing. To do this, it is necessary to fabricate an electroplated diamond tool with high form accuracy and low run-out. This paper describes a tool-making method for high precision grinding and the grinding performance of a self-electroplated tool. The ground surface textures, tool performance and tool life were investigated. A ground surface roughness Rz of 0.14 um was achieved. Our results show that the spindle speed, feed rate and cross feed affected the surface texture. One tool could finish 5000mm^2 of die steel surface without any deterioration of the ground surface roughness.

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NOMENCLATURE

F = tool feed rate
h = depth of cut
l_R = travel length per spindle rotation
l_U = sweep length per period of ultrasonic vibration
P = cross feed
Rz = roughness (maximum height of profile)
S = spindle speed

1. Introduction

Dies for injection molding parts require a high quality surface finish in terms of both appearance and integrity. In particular, the tolerances for the roughness and geometrical deviations of dies used for transparent plastic parts, such as dials of a cellular phone and light guide plates of LCDs, are tight. In order to finish the die, manual polishing by a skilled worker is required after the machining processes, such as electro discharge machining (EDM) and milling. Manual polishing improves the surface roughness but degrades the flatness. Manual polishing is also time consuming (about several days) and expensive. Therefore, it is necessary to establish a machining process to finish dies without manual polishing.

Diamond has superior characteristics for tools, such as high hardness, high thermal conductivity and sharp edges. It can grind difficult-to-machine materials such as ceramics and carbide.[1,2] However, it is not appropriate for steel grinding because of the excessive wear due to diffusion of carbon into the bulk steel and chips.

Ultrasonically assisted machining (USM) methods are suitable to precisely machine difficult materials. The unique aspects of USM are as follows: (a) ultrasonic vibrations increase the cutting speed, and (b) the vibrations supply cutting fluid between the tool and workpiece. As a result, the ultrasonic vibrations of the tool produce fine surfaces and reduce the cutting forces.

A previous report [3] used ultrasonically assisted diamond face grinding for die steel without severe abrasive wear. A surface gloss and roughness of 0.4 μm Rz was obtained. However, ultrasonic spindles have large tool run-out (more than 10 μm) whereas accurate tool geometries and small run-outs are necessary for high precision 3D form machining.[4]

In this study, a tool-making technique and grinding operation are proposed to improve the tool geometry and run-out. We manufacture a self-electroplated diamond tool using an electroplating method and conduct a face grinding experiment with 60-kHz longitudinal ultrasonic vibrations to investigate its performance.

2. Principles of ultrasonically assisted machining

Ultrasonic-assisted machining is a new and promising technique to reduce machining forces and tool wear. This technique uses a high-frequency (above 20 kHz) and low amplitude vibration for the machining process. Figure 1 presents an illustration of one-dimensional vibration cutting. The cutting tool begins to oscillate from the origin, *O*, and then proceeds towards the workpiece with a cutting velocity, *V*, making initial contact with the workpiece at point *A*. The impact force forms chips. Next, the rake face of the cutter separates from the workpiece since the velocity of the cutter exceeds that of the workpiece. This process then repeats: the cutter returns to the workpiece and makes contact with it again.

The effects of ultrasonic-assisted machining are follows.

1. The cutting speed is increased by the ultrasonic vibrations.
2. In non-continuous cutting, the lubrication effects are improved since the cutting fluid reaches the cutting zone.
3. The cutting force is decreased.
4. Less heat is generated compared with conventional cutting.

3. Experiment

3.1 Tool electroplating

An electroplating liquid was placed in an electroplating bath along with two Ni plates as anodes. The cylindrical carbide substrate (cathode) was placed in the center of an abrasive filter. The abrasive filter was then inserted into the electroplating bath. The diamond abrasive grain size was #100/120 (the average grain diameter was 150 μm). Figure 2 shows a schematic view of the electroplating bath and Fig. 3 shows the carbide substrates. The shaded areas of Fig. 3 indicate where nickel was electroplated onto the carbide substrates in the bath; the remaining areas were covered with a mask. The electroplating procedure and conditions are listed in Tables 1 and 2.

Figure 4 compares the appearance of the end faces of (a) electroplated and (b) commercial tools. The grinding particle concentrations were 150 (self-electroplated) and 175 (commercial).

3.2 Grinding apparatus

The grinding experiments were conducted with an NC milling machine equipped with an ultrasonic spindle system (Takesho, Japan). The ultrasonic spindle system was comprised of an ultrasonic spindle, a power supply and a motor speed controller. The ultrasonic spindle system could oscillate tools in the axial direction and rotate them up to 10,000 min^{-1}. Figure 5 shows a schematic illustration of the ultrasonically assisted grinding (USG) system. The grinding tool was the self-electroplated tool described above. The tool diameter was 2 mm and the grain size was #100/120 with an average diameter of 150 μm. The tool was trued before the grinding experiment with a green carbide (GC) wheel on the machine.

3.3 Experimental procedure

The workpiece material was die steel NAK80 (Daido Steel) with HRC40, which is typical for injection molding (*e.g.*, light transmitting parts for cellular phones). The roughness *Rz* (maximum profile height) was nearly 2 μm before the experiments. The workpiece was fixed on the machine table and the cutting tool was fed at the nominal cutting speed in the X- and Y-axis directions, rotated and vibrated in the Z-axis direction ultrasonically at 60 kHz. Figure 5 shows a schematic of the tool path used to face grind a workpiece surface.

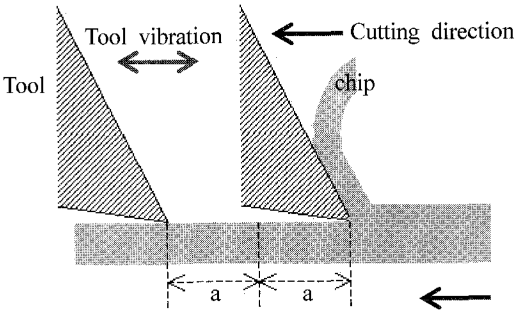


Fig. 1 One-dimensional vibration cutting

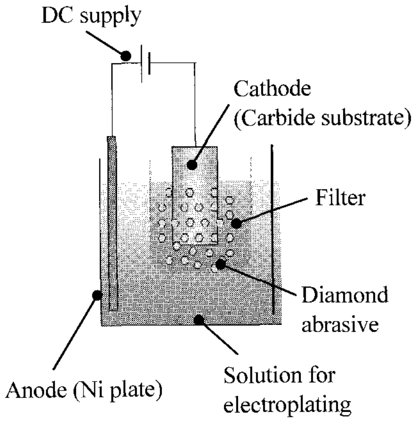


Fig. 2 Electroplating bath schematic

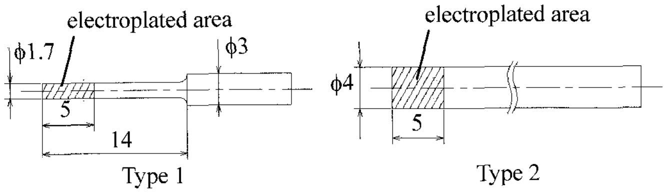


Fig. 3 Carbide substrate design for the electroplated tool

Table 1 Electroplating procedure

Process	Chemical	Conditions
Degreasing wash	Surface acting agent solution	318 K, 5 min
Electrolytic degreasing	Surface acting agent solution with sodium nitride	318 K, 5 A/dm^2 1 min
Etching	Solution of ammonium fluoride and hydrochloric acid	Room temp. 1 min
Electroplating (base)	Solution of nickel chloride	318 K, 2 A/dm^2 10 min
Electroplating (bonding)	Solution of nickel chloride	318 K, 2 A/dm^2 20 min
Electroplating (fitting)	Solution of nickel chloride	318 K, 2 A/dm^2 3 hours

Table 2 Electroplating conditions

Liquid temperature	318 K
Liquid pH	4.5 ~ 5
Current density	2 A/dm^2
Solution	Solution of nickel chloride
Electroplated abrasive	TOMEI diamond #100/120

In Various experiments were conducted with the following goals:

- to investigate the grinding performance of a self-electroplating tool, and
- to determine the effect of the grinding parameters (*e.g.*, spindle speed, tool feed rate and cross feed).

After grinding, the ground surface profiles were measured with an instrument (Surfcom570A, Tokyo Seimitsu Co., Ltd, Japan) and the surface gloss was observed. Generally, a "mirror surface" is defined as a surface with less than a 0.1-μm-*Rz* surface roughness.[5] A glossy surface with more than a 0.1-μm-*Rz* surface roughness is known as "quasi-mirror surface". Surface photographs were taken with a digital camera. A microscope (VHX-200, Keyence, Japan) equipped with a zoom lens (100 – 1000 ×) was used to observe the tool end face topography and ground surface. A laser displacement meter was used to measure the tool vibration amplitude.

4. Results

Various grinding experiments were conducted to investigate the performance of the tool.

4.1 Endurance test

An endurance test of the tool was conducted to determine the tool life. Table 3 shows the experimental parameters for the endurance test. A cross feed of $P = 20$ μm was used to grind a reference surface used to measure the roughness. The other surfaces were ground using $P = 40$ μm.

Figure 6 shows microphotographs of the tool end face before and after the endurance experiment. Figure 7 shows the relationship between the process time and roughness *Rz*. In Fig. 6, the tool was worn out after the endurance test and some abrasive particles were missing. In Fig. 7, the roughness *Rz* changed from 0.33 to 0.71 μm when the process times exceeded 150 minutes.

The results show that tool life was as long as 150 minutes, corresponding to a finished area of 5000 mm.[2] Such a tool could finish half of a cellular phone mold.

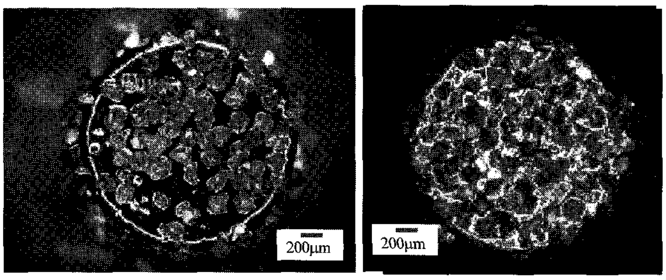
4.2 Grinding parameter effects

4.2.1 Spindle speed

The tool performance at various spindle speeds was investigated. The experimental conditions are listed in Table 4. Figure 8 shows a surface photograph, microphotograph and 2D profile taken along the feed direction during the spindle speed tests. The ground surfaces could reflect the background characteristics, but the roughness of their surfaces was greater than 0.1 μm. In other words, these were quasi-mirror surfaces. The surface roughness of the $S = 9000$ min^{-1} case was the worst. The amplitude of the spindle vibrations increased with the spindle speed. When $S = 9000$ min^{-1}, the cutter path generated a periodical pattern. The wavelength of the surface profile was equal to the travel length per spindle rotation (l_R), defined as

$$l_R = \frac{F}{S} \quad \text{mm} \tag{1}$$

where F is the feed rate (mm/min) and S is spindle speed (min^{-1}). The above result illustrates that the spindle vibration increased the roughness *Rz* of the ground surface.



(a) electroplated tool (Type 1) (b) commercial tool

Fig. 4 Microphotographs of grinding tools

A short wavelength unevenness existed on the surface profiles. This unevenness was equal to the sweep length per period of ultrasonic vibration (l_U), defined as

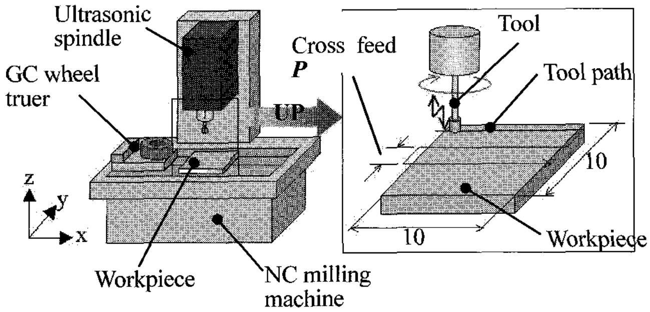
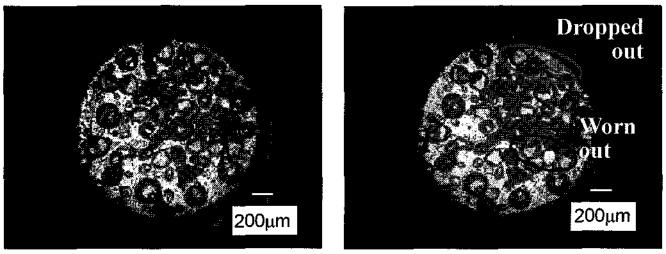


Fig. 5 Schematic of the ultrasonically assisted grinding apparatus and example tool path

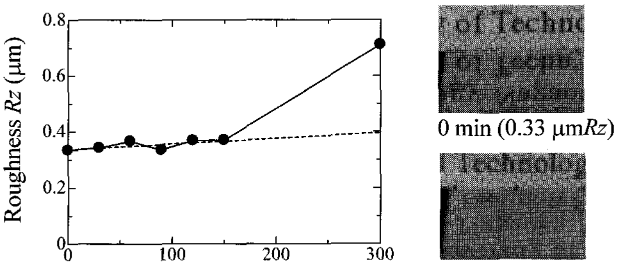
Table 3 Conditions for the tool endurance test

Workpiece	Material	NAK80 (HRC40)
Tool	Material	Tungsten carbide
	Diameter	ϕ2 (Type 1 of Fig. 3)
	Abrasive	SD #100 (Ave. dia. 150 μm)
Cutting conditions	Spindle speed *S*	4000 min^{-1}
	Depth of cut *h*	10 μm
	Cross feed *P*	20, 40 μm
	Feed rate *F*	1000 mm/min
	Cutting fluid	Suncut EF-10 (JIS N4-7)
Vibration conditions	Frequency	60 kHz
	Amplitude	1 μm



(a) before grinding (b) after grinding for 300 min

Fig. 6 Microphotographs of the tool end face



0 min (0.33 μm*Rz*)

300 min (0.71 μm*Rz*)

Fig.7 Relationship between the process time and roughness *Rz*. Grinding conditions: $S = 4000$ min^{-1}, $F = 1000$ mm/min, $P = 40$ μm

$$l_U = \frac{2\pi r \times 10^3 \cdot S}{60 f} \quad \mu\text{m} \qquad (2$$

where f is the ultrasonic vibration frequency (Hz) and r is tool radius (mm). The above result indicates that only one grain was involved in the grinding process. After the grinding process, teeth marks remained on the ground surface. The height of the evenness was measured from the surface profile, and the theoretical height was calculated. We assumed that the tip radius of the grain was 200 μm and that one grain performed the grinding process. We ignored the feed effects the feed was very slow compared to the spindle speed. The theoretical height of the profile elements h_{th} was

$$h_{th} = \frac{1}{8R} l_U^{\ 2} = \frac{1}{8R}\left(\frac{2\pi r \times 10^3 \cdot S}{60 f}\right)^2 = \frac{1370 \cdot r^2 \cdot S^2}{f^2 \cdot R} \quad \mu\mathrm{m} \qquad (3)$$

where R is tip radius of the grain (μm). Figure 9 shows a model of the surface topography and Fig. 10 shows the relationship between the height of the profile elements and the spindle speed. The experimental results were similar to the theoretical values, which again indicated that one grain was involved in the grinding process.

4.2.2 Cross feed

The tool performance was investigated at various cross feeds. The experimental conditions are listed in Table 4. Figure 11 shows a surface photograph, microphotograph and 2D profile taken along the feed direction during the cross feed tests. The ground surfaces had an Rz roughness of 0.37 – 0.40 μm, so they were quasi-mirror surfaces. The surface ground at P = 10 μm had some scratches, which appear as circles in Fig. 11(b), whereas the surface ground at P = 30 μm had few scratches. Tip hammering caused the surface scratches since the number of scratches increased as the contact time was lengthened.

4.2.3 Feed rate

The tool performance was investigated at various feed rates. The experimental conditions are listed in Table 4. Figure 12 shows a surface photograph, microphotograph and 2D profile taken along the feed direction during the feed rate tests. The ground surfaces were quasi-mirror surfaces. The surface roughness obtained for F = 1500 mm/min, when the cutter path generated periodic patterns, was the worst. The observed wavelength of the surface profile was equal to the travel length per spindle rotation (l_R) calculated from Eq. (1). Reticulated marks were also observed on the surface ground F = 1500 mm/min. The surfaces ground at F = 500 and 1000 mm/min had some scratches, which appear as circles in Fig. 12(b), due to tip hammering.

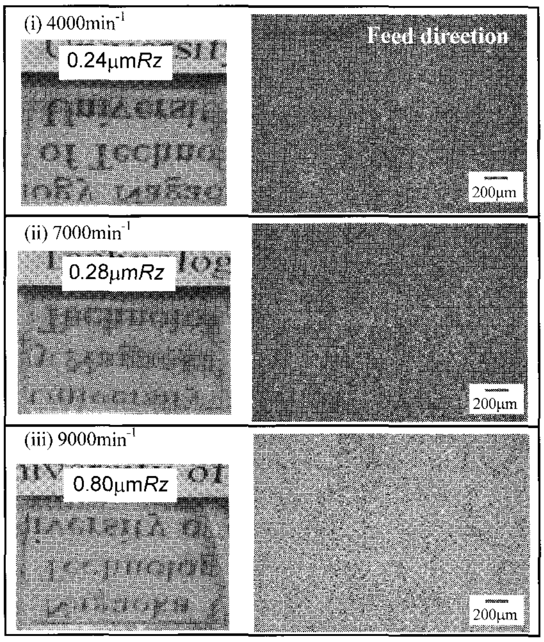
Table 4 Conditions used to determine the effects of the grinding parameters

Workpiece	Material	NAK80 (HRC40)
	Cell size	10 × 10 mm
Tool	Material	tungsten carbide
	Diameter	ϕ2
	Abrasive	SD #100 (Ave. dia. 150 μm)
Cutting conditions	Spindle speed S	4000*, 7000, 9000 min^{-1}
	Depth of cut h	10 μm
	Cross feed P	10, 20*, 30 μm
	Feed rate F	500, 1000*, 2000 mm/min
	Cutting fluid	Suncut EF-10 (JIS N4-7)
Vibration conditions	Frequency	60 kHz
	Amplitude	1 μm

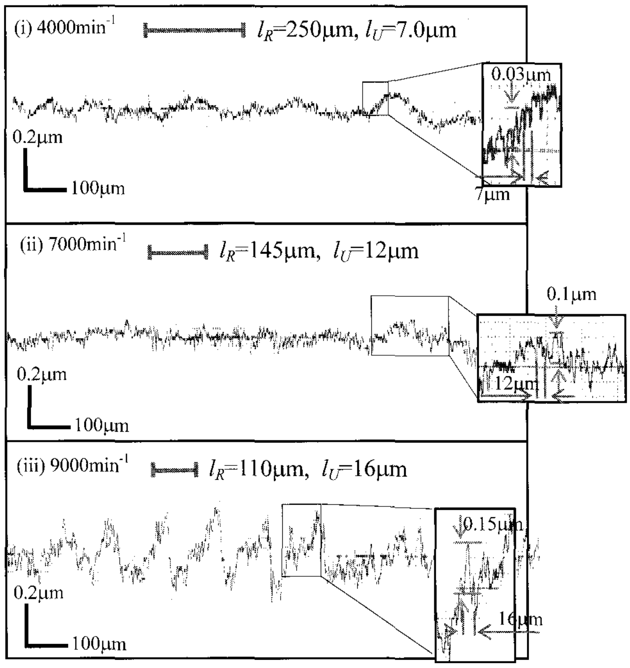
4.3 Machining test using a single-grain tool

In Section 4.2.1, we indicated that only one grain was involved in the grinding process. To investigate this phenomenon, grinding tests were conducted using a single-grain tool made with the Type 2 carbide substrate shown in Fig. 3. Figure 13 shows a microphotograph of the single-grain electroplated tool. The grain was located 1.2 mm from the tool center.

Figure 14 shows microphotographs of the ground surfaces that were produced before truing the tool. The ground surfaces had reticulated marks, which became more noticable as the feed rate or cross feed rate increased. The ground surface marks were similar to those produced by an ordinary electroplated tool.



(a) Photograph, roughness and microphotograph of the ground surfaces



(b) Profile of the ground surface

Fig. 8 Results of the spindle speed tests

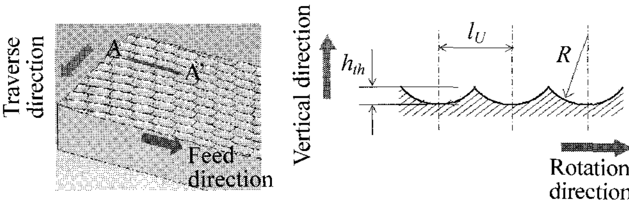


Fig. 9 Geometry of theoretical surface texture ground using ultrasonic assisted grinding

Figure 15 shows images of the ground surfaces that were produced after truing the tool. The ground surfaces had surface roughness of 0.14 μm Rz and 0.17 μm Rz, and the gloss of the surface was superior compared to those produced with an ordinary electroplated tool. Therefore, even if only a few grains are active, the tool can produce "quasi-mirror surface grinding". A truing operation was necessary to perform the mirror surface grinding.

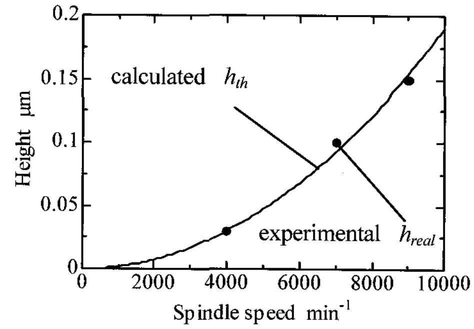
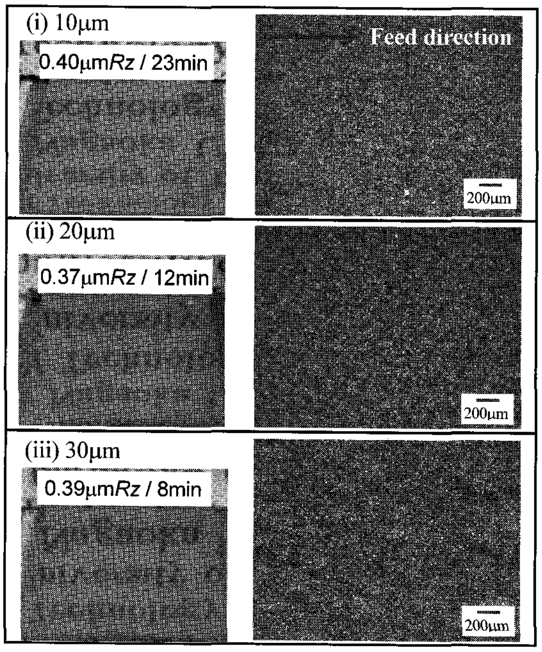
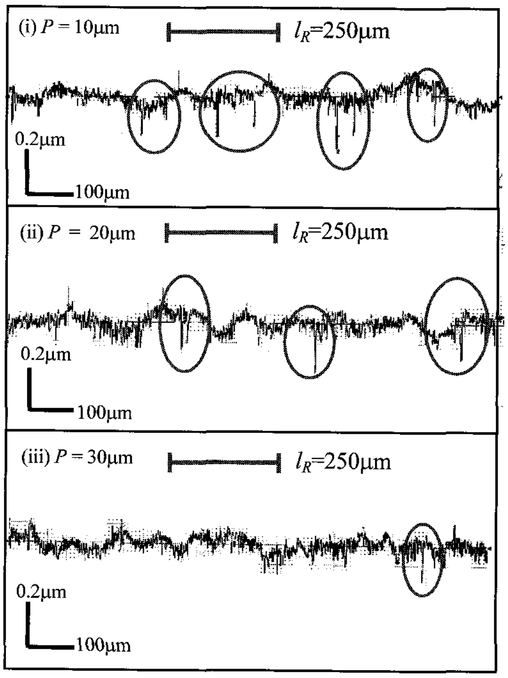


Fig.10 Relationship between the profile element height and spindle speed

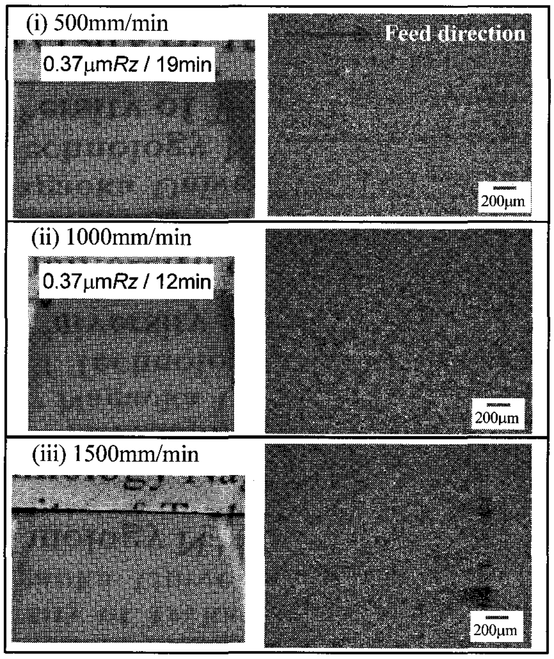


(a) Photograph, roughness and microphotograph of the ground surfaces

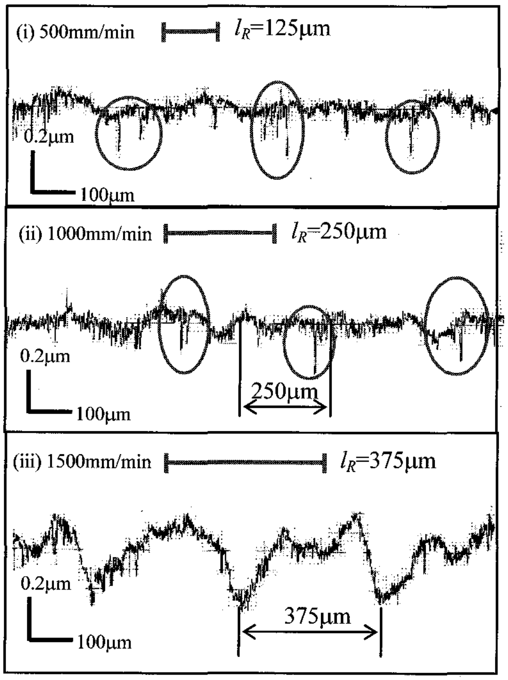


(b) Profiles of the ground surfaces

Fig. 11 Results of the cross feed tests



a) Photograph, roughness and microphotograph of the ground surfaces



(b) Profiles of the ground surfaces

Fig. 12 Results of the feed rate tests

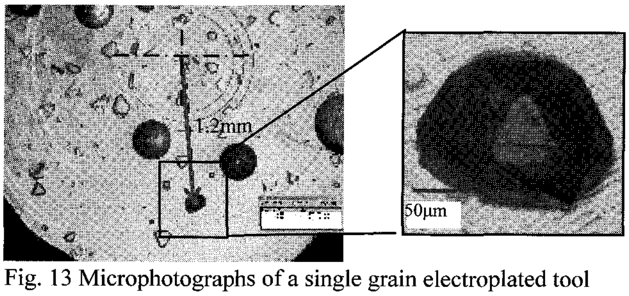


Fig. 13 Microphotographs of a single grain electroplated tool

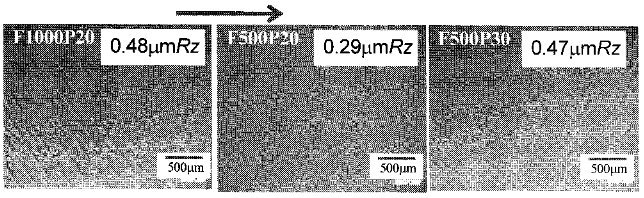


Fig. 14 Microphotographs of a surface ground by a single- grain electroplated tool (before truing)

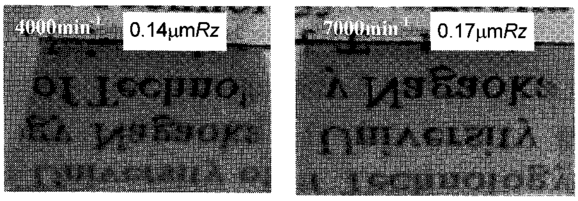


Fig.15 Photographs of a ground surface finished by a single grain electroplated tool (after truing)

5. Conclusions

The following conclusions about ultrasonically assisted diamond grinding of die steel can be drawn.

1. We established the procedure used to manufacture electroplated diamond tools. The performance of these tools was the same as that of commercial tools. A tool endurance test proved that the tool life was equal to that required to finish half of a cellular phone mold.
2. Experiments were conducted to investigate the effects of the grinding parameters (*e.g.*, spindle speed, cross feed and feed rate). As the spindle speed increased, the surface became worse due to the amplitude of the spindle vibration. We noticed scratches when the surface was ground at $F = 500 - 1000$ mm/min for $P = 10$ mm, which were caused by tip hammering since the number of scratches increased as the contact time was lengthened.
3. Grinding tests were conducted with a single grain tool. The results showed that the surface marks were similar to those produced by ordinary electroplated tools. A ground surface roughness of 0.14 μm *Rz* was obtained and the surface gloss was superior compared to surfaces produced by ordinary electroplated tools. Thus, even if only a few grains are active, the proposed electroplated diamond tool could generate a "quasi-mirror surface."

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