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Ductile regime turning at large tool feed

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Abstract

Ductile regime turning is a new technology for obtaining a crack-free surface on brittle material. However, the fundamental obstacle for industrial application of this technology is diamond tool wear. This problem is difficult to solve for existing methods of turning with round-nosed tools due to limitation on tool feed. In this paper, ductile regime turning using the straight-nosed diamond tool is proposed. This method enables thinning of undeformed chip thickness in the nanometric range and at the same time provides significant cutting width ensuring plain strain conditions. Adopting a small cutting edge angle enables ductile regime turning at a large tool feed up to a few tens of micrometers. Single crystal silicon is machined and chip morphology and machined surface texture are examined for clarifying the brittle–ductile transition mechanism. Ductile surface with nanometric roughness is obtained and generation of plastically deformed continuous chips is confirmed.

Keywords: Diamond turning; Brittle material; Ductile regime machining; Brittle–ductile transition; Tool feed

1. Introduction

Recently, various kinds of brittle materials such as optical crystals, glasses, and advanced ceramics are applied more and more in the optical and electronics industries. Most of these applications require a crack-free surface. Traditional methods to obtain such surfaces are grinding and lapping followed by polishing. Recently, diamond turning has enabled direct fabrication of mirror-like surface without subsequent polishing by controlling the cutting mode to be ductile. Since diamond turning has many advantages, such as high machining accuracy and ease of numerical control, it is a preferable method especially for manufacturing components of complex shapes. Still, various problems exist in industrial application of ductile regime turning. One of those problems is severe wear of diamond tools because most brittle material has a higher hardness than metal [1]. Tool wear not only raises machining cost, but also degrades product quality.

Most available literature on ductile regime turning is concerned with the round-nosed diamond tool [2–5], the machining model of which has been put forward by Blackley et al. [4]. On occasion of turning with the round-nosed tool, undeformed chip thickness varies along the cutting edge. Hence, ductile regime turning does not mean that the material of the whole region is removed in ductile mode. A truly ductile response occurs only along the tool tip apex where the undeformed chip thickness is smaller than a critical value d_c (critical chip thickness), while upper material is fractured. Thus, a transition point corresponding to d_c exists on the uncut shoulder. A crack-free surface can be obtained if this transition point position is high enough and the fracture does not replicate into the machined surface plane. However, for a given d_c, the tool feed must be kept very small in order to elevate the transition point position. Maximum tool feed for obtaining a homogeneous ductile surface on all crystallographic orientations of germanium [2] and silicon [5] has been reported to be 1 μm. Restriction on tool feed has been considered as a ‘‘process limit’’ for ductile regime turning technology [3].

For a certain machining area, a small tool feed leads to a long cutting distance. During face turning, the relationship between cutting distance Γ and tool feed f can be described in Eq. (1)

$$\Gamma = \frac{\pi r^2}{f} \tag{1}$$

where r is workpiece radius. Since tool wear volume increases with respect to cutting distance, given other conditions are constant, a smaller tool feed corresponds to

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greater tool wear. The tool wear problem becomes particularly serious with large workpiece radius r because tool wear dominates profiling errors and surface roughness as cutting distance increases [6]. A small tool feed also increases machining time and lowers machining efficiency.

This paper proposes ductile regime turning using the straight-nosed diamond tool. The objective is to realize ductile regime turning under large tool feed. Single crystal silicon is machined and fundamental machining characteristics are investigated.

2. Machining model

The machining model of straight-nosed diamond tool is schematically shown in Fig. 1. In this model, undeformed chip thickness h becomes uniform along almost the entire width of the main cutting edge. Therefore, the cutting mode also becomes uniform. Undeformed chip thickness h is determined by tool feed f and cutting edge angle κ, as described in Eq. (2)

$$h = f \sin \kappa \tag{2}$$

By controlling the cutting edge angle κ to be small enough, an extremely small undeformed chip thickness h can be obtained even at a large tool feed f. Here, if the critical tool feed for ductile regime turning is f_c, the relationship among f_c, d_c and κ can be described in Eq. (3)

$$f_c = \frac{d_c}{\sin \kappa} \tag{3}$$

Accordingly, for a given d_c, f_c is inversely proportional to κ when κ is small enough, as described in Eq. (4)

$$f_c \propto \frac{1}{\kappa} \tag{4}$$

This implies that ductile regime turning under a large tool feed becomes possible by adopting a very small κ.

Compared to turning with the round-nosed tool, the proposed method has consistency in chip thickness over the entire cutting width hence better approaching orthogonal cutting. Orthogonal cutting over a large cutting width b provides the plain strain condition. The plain strain condition will contribute to maintain hydrostatic pressure in the cutting region, which is necessary for ductile material removal. Furthermore, this method provides an effective means for studying brittle–ductile transition. Due to consistency in undeformed chip thickness and cutting mode, the machining model is simpler than that of the round-nosed tool. Critical chip thickness d_c can be obtained directly and precisely by measuring critical tool feed f_c on the machined surface.

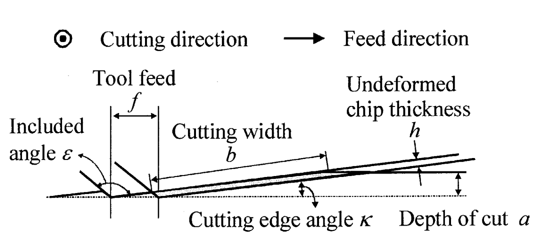


Fig. 1. Machining model of the straight-nosed tool.

3. Experimental procedure

3.1. Machine tool

The experiment is carried out on a TOYODA ultra-precision lathe, the schematic of which is shown in Fig. 2. It has a hydrostatic bearing spindle and two perpendicular slide tables along the X-axis and Z-axis. The slide table driving system has a two-level structure: a hydraulic system for coarse motion and a servomotor system for fine motion. A precision tool post is installed on the Z-axis table. This tool post can rotate along the vertical B-axis and enable cutting edge angle adjustment with resolution better than 0.01°. Four air mounts are set under the machine base to isolate environmental vibration.

3.2. Cutting edge angle measurement

To measure the small cutting edge angle precisely, a transcription method is used. First, after tool presetting, a plunge cut is performed on an aluminum workpiece. Subsequently, the aluminum surface is measured using a surface measurement instrument (Form Talysurf) and the profile of the plunge cut surface is obtained. Finally, the cutting edge angle can be calculated simply from the surface profile. An example of the plunge cut profile is shown in Fig. 3. The cutting edge angle calculated from the above profile is 0.25°.

3.3. Diamond tool

A straight-nosed single crystal diamond tool having a 1.25 mm main cutting edge, a 135° included angle, a 0° rake

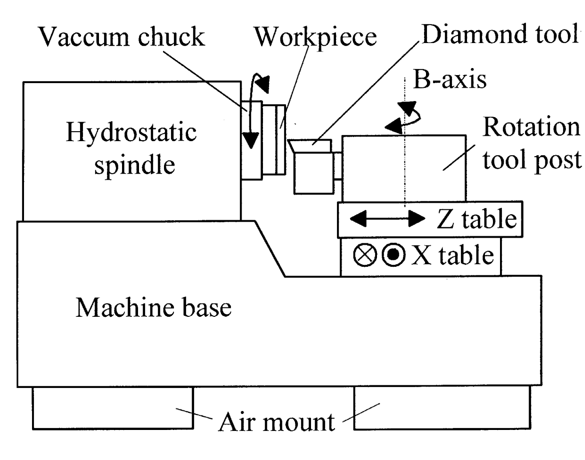


Fig. 2. Schematic diagram of the experimental set-up.

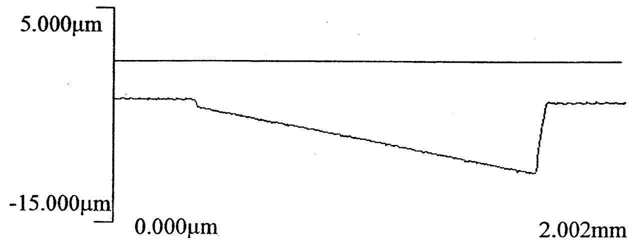


Fig. 3. Surface profile of the plunge cut for measuring the cutting edge angle ($\kappa = 0.25°$).

angle, and a 6° relief angle is used for cutting. In order to adjust the rake angle to negative values, steel spacers with different gradients are fixed between the tool shank and tool post. Before cutting, the tool is examined using a scanning electron microscope (SEM). Fig. 4 shows an SEM photograph of the main cutting edge. The edge appears to be smooth and sharp without any visible defects even under 10 000× magnification. The cutting edge sectional profile is measured using SEM-based three-dimensional analysis equipment having two electron detectors. Edge radius is estimated to be 50 nm.

3.4. Specimen

Silicon (1 1 1) and (1 0 0) wafers are used as specimens. These wafers are 76.2 mm in diameter and 1.2 mm in thickness, respectively, with lapped finishes. Wafers were bonded on diamond turned aluminum blanks using heat-softened glue and then vacuum chucked on the machine spindle. For the purpose of removing the damaged layer, a facing cut is performed with other diamond tools and about 50 μm depth of material is removed, providing a mirror-like surface. After the turning experiment, some machined wafers are sliced to suitable sizes for SEM observation and atomic force microscope (AFM) measurement.

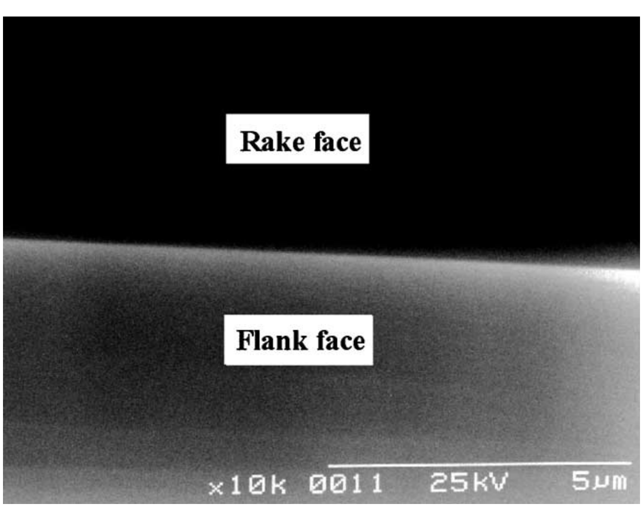


Fig. 4. SEM photograph of the main cutting edge of a diamond tool.

3.5. Cutting conditions

Face turning is performed. Undeformed chip thickness h is varied from some nanometers to 1 μm by adjusting cutting edge angle κ and tool feed f, respectively, in the range of 0.1–2°, and 1–40 μm. The machine spindle rotation rate is 1500 rpm. Depth of cut a is varied in the range of 1–5 μm. Dry cutting is performed for the purpose of collecting chips for observation. Nomarski differential interference microscope, SEM, Form Talysurf, and AFM are each used for observation and measurement of machined surfaces. Cutting chips are observed using SEM.

4. Results and discussion

4.1. Critical chip thickness of brittle–ductile transition

For ductile regime turning, it is important to determine quantitatively critical chip thickness d_c of brittle–ductile transition. In the present experiment, d_c is measured using the following method. First, the cutting edge angle is preset to approximately 1°. Then, a facing cut is performed with continuously varied tool feed. An example of the Nomarski micrograph of the surface machined under such a condition is shown in Fig. 5. As tool feed is increased from left to right, the cutting mode transits from ductile to brittle. Microfractures begin to occur at a critical tool feed f_c. Value of critical chip thickness d_c is calculated from f_c from Eq. (3). Ductile to brittle transition leads to significant surface roughness variation. An example of the surface profile machined under continuously varied tool feed is shown in Fig. 6. The surface roughness (peak-valley height) increases from some nanometers to approximately 1 μm as the cutting mode transits from ductile to brittle.

Brittle–ductile transition characteristics are found to vary with crystallographic orientation even on the same silicon wafer. The polar plot of critical chip thickness d_c versus crystallographic orientation of silicon (1 1 1) wafer is shown in Fig. 7. Symmetrical peak-valley distributions of d_c are observed in a circumferential orientation. Three large valleys and three small valleys appear during one wafer revolution. Directions corresponding to minimum critical chip thickness d_{cmin} are $\langle \bar{2}\,1\,1 \rangle$, $\langle 1\,1\,\bar{2} \rangle$, and $\langle 1\,\bar{2}\,1 \rangle$ orientations. These directions are the most difficult in which to obtain a crack-free surface. A similar phenomenon is observed for the (1 0 0) wafer, where minimum critical chip thickness appears along four [1 0 0] orientations. Crystallographic dependence of critical chip thickness causes anisotropy in ductile regime machinability. This phenomenon has been explained qualitatively through analyzing the slip system [7] and cleavage system [8] by Shibata et al. and Blackley et al., respectively. Here, results shown in Fig. 7 quantitatively illustrate that in order to avoid anisotropy and obtain homogeneous ductile crystal surfaces, undeformed chip thickness must be controlled

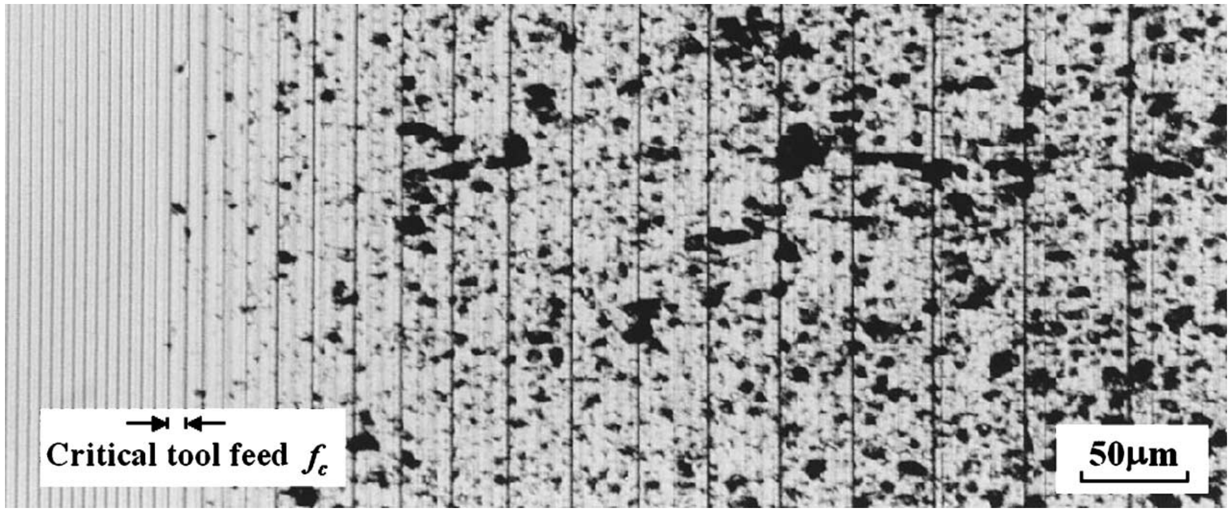


Fig. 5. Nomarski micrograph of the machined surface under continuously varied tool feed for measuring critical chip thickness (silicon (1 1 1), $\langle \bar{2}\,1\,1 \rangle$ orientation, $\kappa = 1.0°$, $\gamma = -40°$).

below minimum critical chip thickness d_{cmin} of all crystallographic orientations.

It is also found that tool rake angle has significant effects on critical chip thickness. Variation in minimum critical chip thickness d_{cmin} of (1 1 1) and (1 0 0) wafers with respect to tool rake angle γ is shown in Fig. 8. It is evident that d_c increases remarkably as rake angle is reduced from 0° to −40° for both wafers. This result is similar in trend to previous studies [2–5], although a much larger negative rake angle is used in the present paper. This suggests that ductile cutting performance of a 0° rake angle diamond tool can be largely improved by only adjusting rake angle to suitable negative values. Moreover, it is notable that difference in d_{cmin} of (1 1 1) and (1 0 0) wafers becomes smaller when larger negative rake angle tools are used and values of d_{cmin} of both wafers exhibit a reverse comparison relationship as the rake angle is changed from 0° to −40°. This implies that the rake angle effect on brittle–ductile transition also has crystallographic effects.

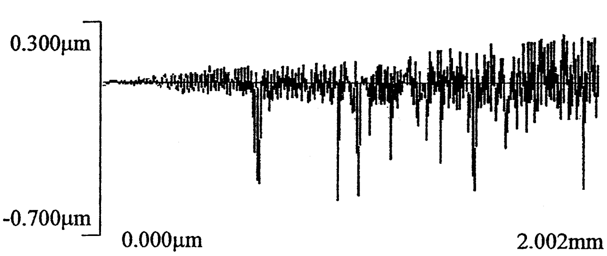


Fig. 6. Surface profile variation in ductile-brittle transition.

4.2. Brittle–ductile transition mechanism

Silicon has a strong directional covalent bond with a diamond structure. The cleavage plane is {1 1 1} and predominant slip system is {1 1 1}[1 1 0]. At room temperature, dislocations are difficult to move; hence silicon

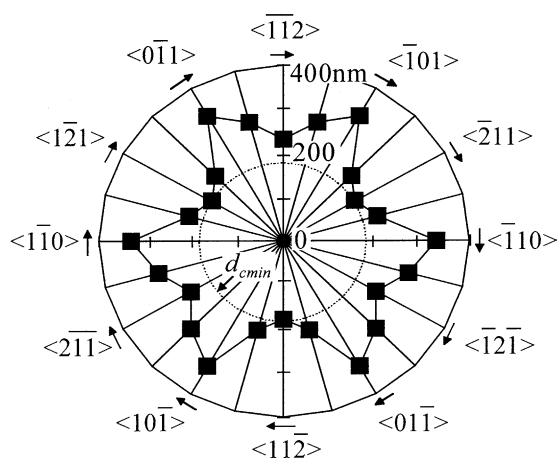


Fig. 7. Crystallographic dependence of critical chip thickness on silicon (1 1 1), $\gamma = -40°$.

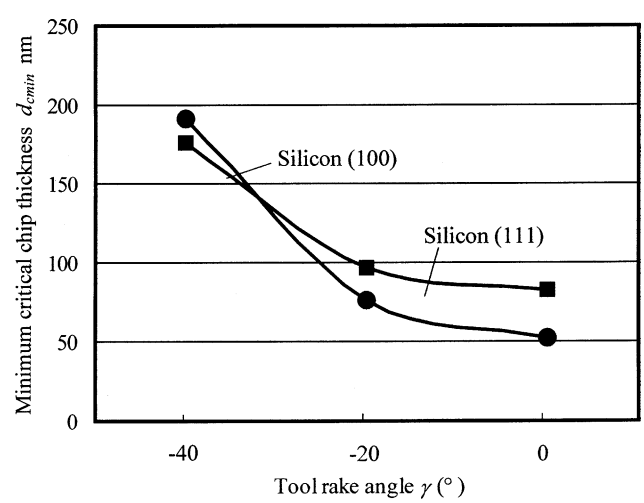


Fig. 8. Effect of tool rake angle on minimum critical chip thickness.

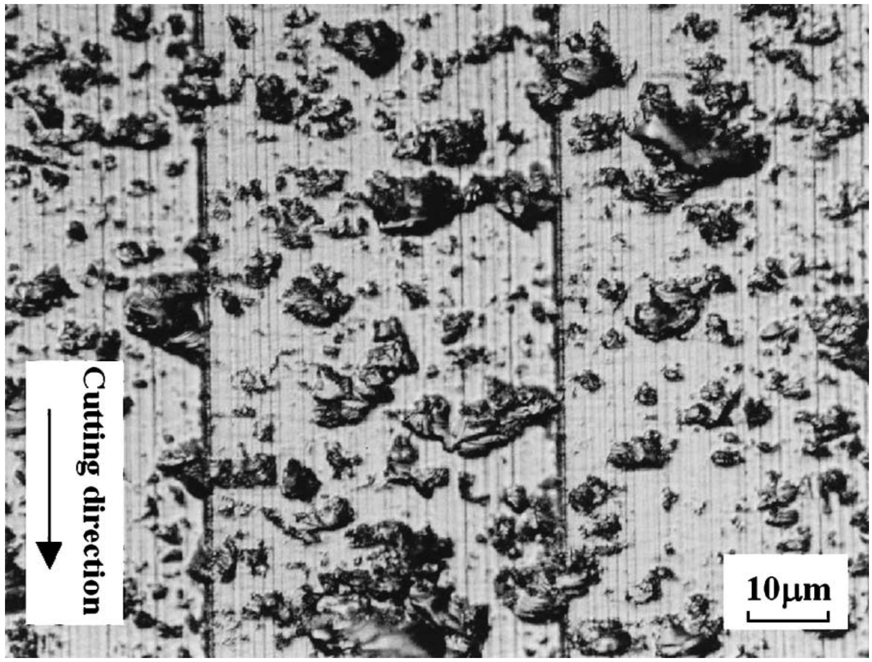


Fig. 9. Nomarski micrograph of a brittle regime machined surface (silicon (1 0 0), $\langle 1\,\bar{1}\,0 \rangle$ orientation, $f = 38$ μm, $\kappa = 1.4°$, $h = 928$ nm, $\gamma = 0°$).

responds in a brittle manner. Although it has been well known that brittle–ductile transition occurs with sufficiently small machining scale, origin of the transition is still unclear. In the present study, to understand the brittle–ductile transition mechanism, both chips and machined surfaces are examined in detail.

The Nomarski micrograph of a typical brittle regime surface is shown in Fig. 9. Parallel dark lines on the surface are tool marks corresponding to tool feed. The surface is severely damaged with micro-craters and cracks, the size of which ranges in the order of 1–10 μm. Detailed observation of a large crater using SEM is shown in Fig. 10. The crater is a few micrometers in depth, several times deeper than undeformed chip thickness. In the crater, layer structures can be observed along some specific directions. An SEM photograph of corresponding cutting chips is shown in Fig. 11. These chips consist of 1–10 μm particles, irregular in shape and having sharp ends, with appearance to similar

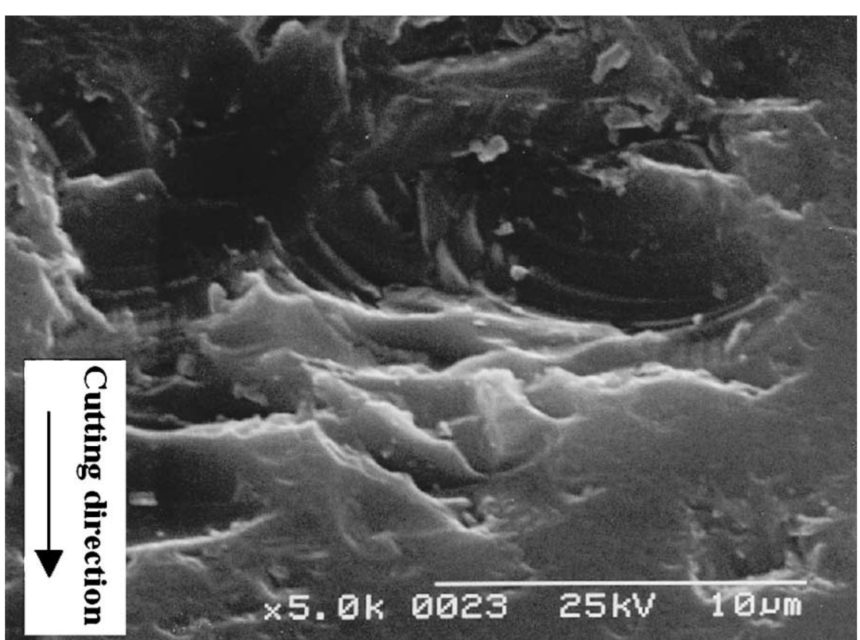


Fig. 10. SEM photograph of a typical micro-fracture on the surface in Fig. 9.

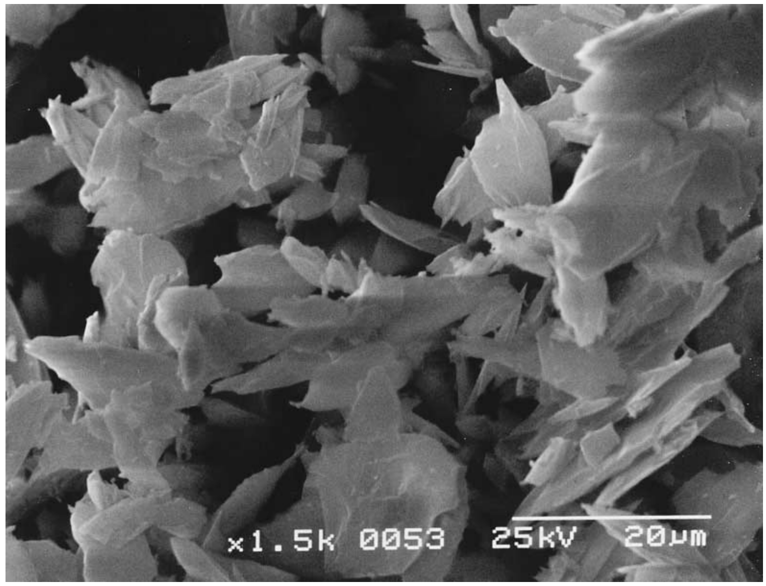


Fig. 11. SEM photograph of the brittle regime chips (conditions are same as Fig. 9).

crushed rock. These kinds of surface fractures and chips imply that brittle fracture is predominant in material removal whereas almost no plastic deformation occurs.

The Nomarski micrograph of a ductile regime machined surface is shown in Fig. 12. The surface is very smooth without any visible damages, although tool feed marks can still be observed. AFM topography of the same surface is shown in Fig. 13. The surface is characterized by regular microgrooves implying that the surface is precisely transcribed by the cutting edge even in the nanometric range. Fig. 14 shows an SEM photograph of the ductile regime chips. These chips are in the form of continuous ribbons similar to those of metal cutting. It is well reflected that plastic deformation occurs dominantly and almost no fracture is generated in this machining regime.

Above results imply that the brittle–ductile transition in the diamond turning process is a transition from tensile cleavage fracture to large-strain plastic deformation. This transition conceivably originates from the stress state transition in the cutting region. When undeformed chip thickness is large, as schematically shown in Fig. 15(a), there exists a concentration region of tensile stress in the vicinity of the cutting edge, whereas most of the upper region is under a low-stress state. Due to low fracture toughness of silicon, cracks

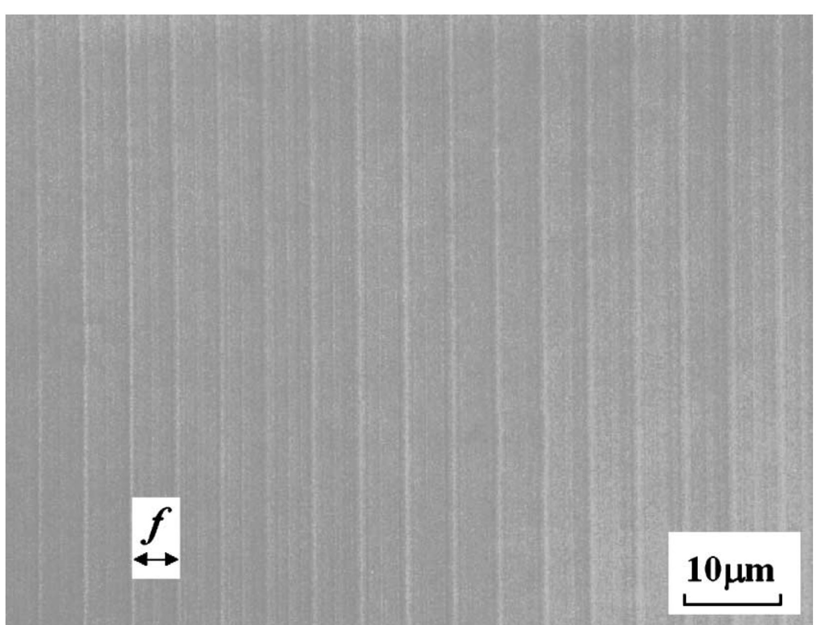


Fig. 12. Nomarski micrograph of a ductile regime machined surface (silicon (1 0 0), $\langle 1\,\bar{1}\,0\rangle$ orientation, $f = 5$ μm, $\kappa = 0.5°$, $h = 44$ nm, $\gamma = -40°$).

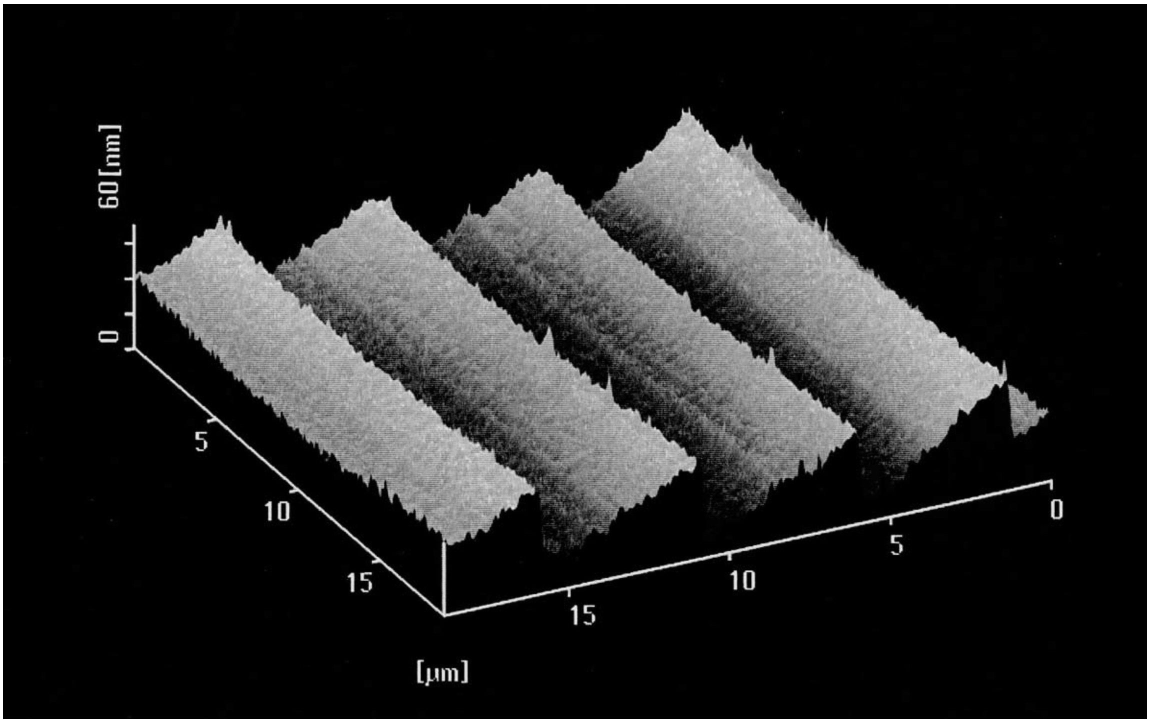


Fig. 13. AFM topography of the ductile regime machined surface in Fig. 12.

will be immediately initiated in the stress concentration region as a tool advances before any plastic deformation occurs. This results in brittle mode material removal, which is similar to the cutting process of ceramics investigated by Ueda et al. [9]. However, different from ceramics cutting, the silicon cleavage system significantly affects the crack propagation path. Thus, cleavage layers along specific directions are liable to be formed inside the crater.

On the other hand, the stress state varies with cutting parameters and cutting edge geometry. As undeformed chip thickness is decreased, the scale of the low-stress region in Fig. 15(a) decreases. When undeformed chip thickness becomes small enough, the entire cutting region will be under the high-stress state. Moreover, since a common diamond tool usually contains an edge radius of some tens of nanometers or larger, an extremely small undeformed

Fig. 14. SEM photograph of the continuous ribbon chips in ductile regime turning (conditions are same as Fig. 12).

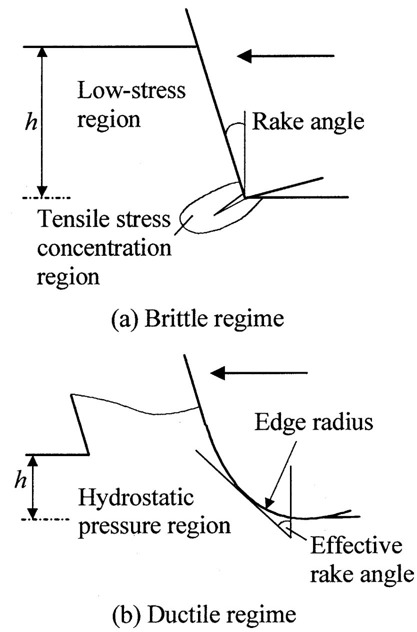


Fig. 15. Schematic illustration of the stress state in brittle–ductile transition: (a) brittle regime; (b) ductile regime.

chip thickness approaches the same order of cutting edge radius, as shown in Fig. 15(b). In this case, the cutting edge effects become significant and cannot be neglected as in the brittle machining regime or in traditional metal cutting. Edge radius effects include at least two aspects. First, edge roundness decreases stress concentration and yields a relatively uniform stress field. Second, since the effective rake angle induced by the edge radius becomes a large negative value, material in front of the cutting edge is downward suppressed and the compressive stress component becomes predominant. This provides a stress state similar to the hydrostatic stress field.

As known from the theory of plasticity, magnitude of hydrostatic stress determines the extent of plastic deformation prior to fracture [10]. In other words, hydrostatic pressure determines strain at fracture, which in turn determines material ductility or brittleness. Bridgman proved that various nominally brittle materials are capable of ductile behavior under high external hydrostatic pressure [11]. Castaing et al. found that under hydrostatic pressure, the temperature at which silicon can be plastically deformed was largely lowered [12]. Therefore, with sufficient hydrostatic pressure, plastic deformation will become preferable to crack generation even at a lower temperature and ductile regime material removal can be achieved. This is considered to be the origin of the brittle–ductile transition in diamond turning. The above explanation is consistent with the fact that negative tool rake angle corresponds to larger critical chip thickness than the 0° rake angle because negative rake angle contributes to hydrostatic pressure formation.

Although an extremely high hydrostatic pressure is a prerequisite for ductile regime of brittle material, this hydrostatic pressure can be obtained immediately by decreasing undeformed chip thickness and/or tool rake angle, instead of any externally exposed pressure. Moreover, in the case of turning with a straight-nosed tool, the plain strain condition is considered to aid in maintaining hydrostatic pressure compared to a round-nosed tool, which in turn contributes to ductile material removal. This is proved to some extent after a comparison of values of critical chip thickness of silicon obtained in the present and previous studies [2,3]. It is notable that for most occasions, larger critical chip thickness are obtained through the present method, which is difficult to discount as mere experimental randomness.

4.3. Large tool feed ductile regime turning

As mentioned in Section 1, increasing critical tool feed for ductile regime turning has various advantages concerning tool wear, machining efficiency, and consequent production cost. Diamond turning using a straight-nosed tool provides the possibility of large tool feed ductile regime turning. Theoretically, in Eq. (4), f_c grows infinitely large as κ approaches 0. However, the practical minimum cutting edge angle and maximum tool feed usually depend on machine tool stiffness. For a given depth of cut a, decrease in cutting edge angle κ will increase cutting width b; meanwhile, a large tool feed increases undeformed chip thickness for a given κ. Both factors lead to increased cutting force. Since a

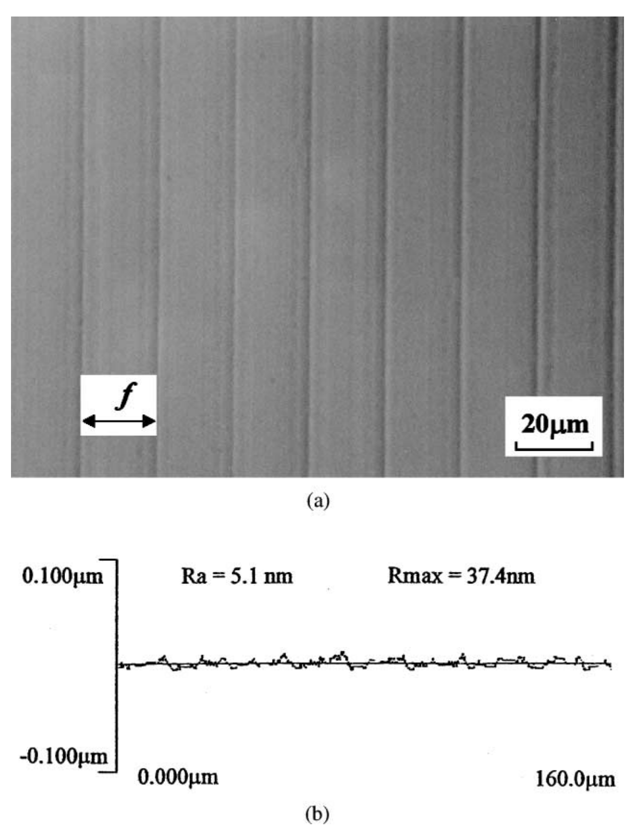


Fig. 16. Nomarski micrograph (a) and profile (b) of the surface machined at a tool feed of 20 μm (silicon (1 0 0), ⟨1 0 0⟩ orientation, $\kappa = 0.1°$, $\gamma = -40°$).

large cutting force is liable to induce machining chatter, very high machine stiffness is required to ensure machining process steadiness at an extremely small cutting edge angle and/or very large tool feed.

Under present machine tool conditions, steady ductile regime turning is realized at cutting edge angles smaller than 0.1° at 1 μm depth of cut. Theoretically, this enables a critical tool feed up to approximately 100 μm for both types of wafers by using a −40° rake angle tool. However, according to the fundamental tool–work transcription mechanism, surface roughness increases with respect to tool feed, as described in Eq. (5)

$$R_{\max} = \frac{f}{\operatorname{ctg}\kappa - \operatorname{ctg}(\varepsilon + \kappa)} \tag{5}$$

where $R_{\max}$ is the peak-valley roughness and ε the included angle as shown in Fig. 1. Therefore, in order to obtain fine surface roughness, smaller tool feed values are preferable rather than an extremely large tool feed value. Fig. 16 shows the Nomarski micrograph and profile of the surface machined at 20 μm tool feed value. The surface is ductile and its profile contains periodical peak-valley waviness corresponding to tool feeds. It has a roughness of 5.1 nm R_a and 37.4 nm $R_{\max}$, which approaches theoretical values.

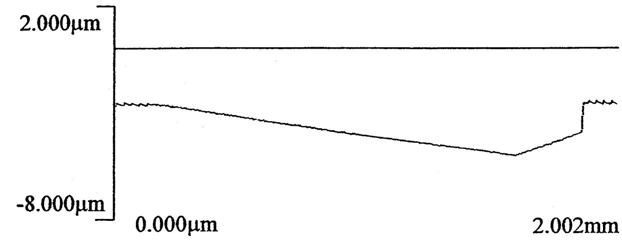
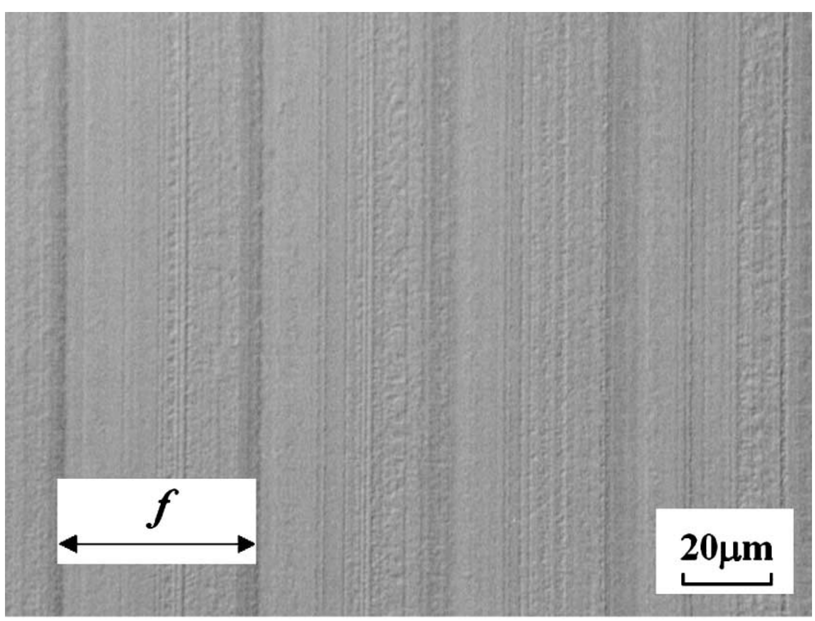
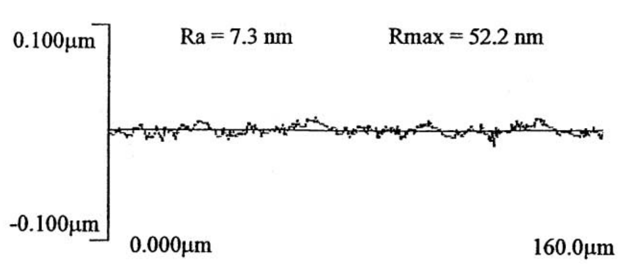


Fig. 17. Plunge cut surface profile of a diamond tool having a large included angle ($\kappa = 0.1°$, $\varepsilon = 179.6°$).

For much larger tool feed, surface roughness will become larger. In those cases, surface roughness can be improved by increasing the diamond tool included angle ε. A large included angle can be immediately obtained by polishing a micro-chamfer, acting as the smoothing edge, on the tip of the present tool. Fig. 17 shows the plunge cut profile of a diamond tool having a 179.6° included angle with a smoothing edge approximately 200 μm in length. Fig. 18 shows the Nomarski micrograph and the profile of the surface



(a)



(b)

Fig. 18. Nomarski micrograph (a) and profile (b) of the surface machined at a tool feed of 40 μm (silicon (1 0 0), ⟨1 0 0⟩ orientation, $\kappa = 0.1°$, $\varepsilon = 179.6°$, $\gamma = -40°$).

machined using this tool at a tool feed value of 40 μm. Even at such a large tool feed, the surface remains very good having a roughness of 7.3 nm R_a and 52.2 nm R_{max}, which is sufficient for various applications such as infrared optical components.

5. Summary

A new method for ductile regime turning brittle material using a straight-nosed diamond tool is proposed. Via adopting small cutting edge angles, this method enables thinning of undeformed chip thickness in the nanometric range and at the same time provides plain strain conditions. Effects of crystallographic orientation and tool rake angle on critical chip thickness of single crystal silicon are investigated. Chips and machined surfaces are examined and the brittle–ductile transition mechanism is discussed from the view of stress state transition. Ductile regime turning is realized at a large tool feed up to some tens of micrometers. Mirror-like surfaces with nanometric roughness are obtained on single crystal silicon and continuous ribbon chip generation is confirmed.

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