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ORIGINAL ARTICLE

Experimental investigation of specific cutting energy and surface quality based on negative effective rake angle in micro turning

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Abstract Since the uncut chip thickness is comparable to the cutting edge radius, in fact, micro cutting is a negative rake angle cutting process. The minimum chip thickness has great effect on the cutting process. This paper presents an experimental investigation of specific cutting energy and surface quality based on the negative effective rake angle in micro turning. A new model is developed to calculate the negative effective rake angle in micro cutting. The effective rake angle is found to be more negative with the decreasing ratio of uncut chip thickness to cutting edge radius. The minimum chip thickness is calculated to be about 0.2–0.3 times of cutting edge radius based on the critical negative rake angle. The turn point of the nonlinear increase of specific cutting energy is observed to be at the critical negative rake angle. The minimum surface roughness also is found to be achieved near the critical negative rake angle.

Keywords Micro turning · Minimum chip thickness · Effective rake angle · Specific cutting energy · Surface roughness

1 Introduction

Micro cutting is capable of producing micro parts with three-dimensional features ranging from a few microns to a few hundred microns in a wide range of materials. Micro cutting process demands the use of small tools and thereby a downscaling of cutting process into micro dimension [1–3]. Although the small size cutting tools can be manufactured, but the cutting edge radius cannot downscale to the same proportion due to the limitation of tool manufacturing technology. The material removal mechanism is significantly different to conventional cutting. The presentation of concern mechanisms such as size effect, negative effective rake angle, and minimum chip thickness often leads to poor surface quality or large burr that cannot meet the functional requirements [4, 5]. A nonlinearly increase in specific energy with decrease of uncut chip thickness is called size effect phenomenon. It is related to the effects of relatively larger cutting edge radius, as well as the workpiece material homogeneity, and isotropic nature is invalid [2–4, 6, 7]. When uncut chip thickness is less than the critical value, no material removal in the form of chip occurs. The minimum chip thickness effect seems to set the lower limit of feasible micro cutting process [8, 9]. Lee [10] pointed out that minimum chip thickness influences the effective rake angle, chip thickness, and specific cutting energy. Liu [11] reported that the micro cutting process is affected by two mechanisms, chip removal and plowing due to the minimum chip thickness effect. The surface quality is affected by a variety of factors including machining parameters, tool geometric, and workpiece material [12–14]. It is found that in micro cutting, the surface roughness at first decreases with feed, reaches a minimum, and then tends to increase with further reduction in feed. Aramcharoen [15] suggested that the plowing at the low feed per tooth increases the surface roughness. The minimum chip thickness also is considered to be responsible for the larger surface roughness [16]. Liu [17] and Zhang [18] pointed out that plastic side flow deteriorates the surface quality. They also established surface roughness prediction models.

In micro cutting, the uncut chip thickness is comparable to the cutting edge radius. The tool cannot be assumed to be perfect sharp. The effective rake angle actually is negative

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and related with the ratio of uncut chip thickness to cutting edge radius. Although the negative effective rake angle is known, but little attention is focused on its quantitative analysis. To get further understand of micro cutting, this paper performs an experimental investigation on the specific cutting energy and surface quality based on negative effective rake angle. A new model is proposed to calculate the negative effective rake angle in micro cutting based on the ratio of uncut chip thickness to cutting edge radius. The minimum chip thickness is calculated based on the critical negative rake angle for chip formation. The negative effective rake angle on specific cutting energy, surface quality, and chip morphology also is studied.

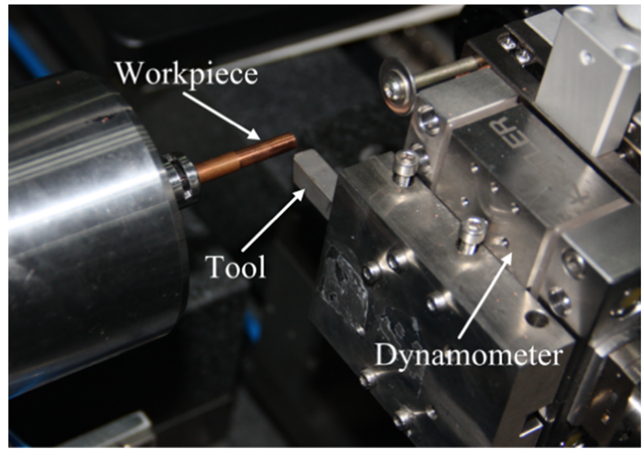


Fig. 1 A view of the experiment setup

2 Experimental setup

The experiments were conducted on a micro turning machine. The machine tool is specifically designed for micro cutting process. It is constructed with air guides that are driven by linear motors. The machine is capable of positioning accuracy and repetition accuracy of ±1 μm. The air bearing spindle can rotate up to 20,000 rpm. The workpiece used in the experiment was an oxygen-free copper bar with a diameter of 6 mm. The cutting tool was PCD micro turning tool. Its rake angle and flank angle are 10° and 5°, respectively. The tool cutting edge angle and cutting edge inclination angle are 45° and 0°, respectively. The tool nose radius r and cutting edge radius r_n were measured by three-dimensional reconstruction with LEICA DVM5000 microscope to be about 40 and 8 μm, respectively. A stereo microscope and image processing system were used for tool setting and turning process monitoring. The cutting tool was fixed on the dynamometer, as shown in Fig. 1. The cutting force was measured by KISTLER dynamometer (9256C1). The sampling rate was set at 30 kHz. The machined surface roughness R_a and R_z were measured by Mahr Perthometer M1. The machined surface and chip morphology were observed by Hitachi S-3400N scanning electron microscope.

Because the tool cutting edge angle k_r is 45°, the feed per rotation f_r and cutting depth a_p were converted to the uncut chip thickness a_o and cutting width a_w, as shown in Fig. 2. It can be formulated as:

$$a_o = f_r \times \sin\ k_r \quad (1)$$

In the experiments, the spindle rotating speed n and cutting width a_w were fixed. The uncut chip thickness a_o was tested at 15 levels. The range of uncut chip thickness was selected to include less than minimum chip thickness and greater than cutting edge radius in the data. The machining parameters are listed in the Table 1 in detail. The experiments were repeated three times, and the mean values were adopted as the experiment results. The turning process was conducted in dry condition. After the tests, the machined surface was cleaned by an ultrasonic cleaning machine.

3 Result and discussion

3.1 Cutting force and specific cutting energy

The cutting force signals contain important information of mechanics and dynamics of the cutting process. The surface quality can also be predicted from the cutting force fluctuation. Moreover, the large cutting force is easy to cause the breakage of micro cutting tool due to its low strength. So the cutting force often is expected to be small in micro cutting. The cutting forces results are shown in Fig. 3. Specific cutting energy is the energy required to remove a unit amount of material. Based on [5], the specific cutting energies can be calculated by dividing the cutting forces by the chip area. It can be formulated as:

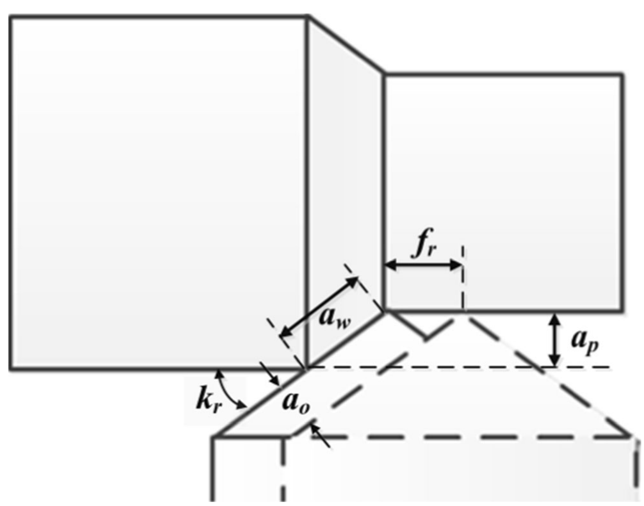


Fig. 2 The parameters of cutting layer

Table 1 The machining parameters

Spindle speed n (rpm)	360
Cutting width a_w (μm)	14.1
Uncut chip thickness a_o (μm)	0.7~14.1
Ratio of a_o/r_n	0.09~1.77

$$S = \frac{F}{a_o \times a_w} \tag{2}$$

where S is the specific cutting energy, F is the cutting force, a_o is the uncut chip thickness, and a_w is the cutting width. Figure 4 shows the specific energy variation.

The cutting force is found to approximately linearly decrease with the reduction of a_o/r_n. This is because the material removal decreases so that less cutting force is needed. However, the specific cutting energy is observed to nonlinearly increase with the decrease of a_o/r_n. When the ratio of a_o/r_n is larger, the specific cutting energy increases slowly. It is about 5.1 J/mm^3 at a_o/r_n of 1.77 and only increases to 8.6 J/mm^3 at a_o/r_n of 0.35. With further reduction of a_o/r_n, the specific cutting energy increases quite rapidly. The maximum specific cutting energy reaches to more than 20 J/mm^3 at a_o/r_n of 0.09. The turning point is at the ratio of about 0.3, as shown in Fig. 4. When a_o/r_n is greater than 0.3, the curve slope is about 2. But as a_o/r_n reduces to less than 0.3, the curve slope increases to 66. This is the size effect phenomenon in micro cutting. The minimum chip thickness is considered to be responsible for it. When the uncut chip thickness reduces to less than minimum chip thickness, the tool cutting edge round plow instead of cut the workpiece. The needed specific energy is larger.

The uncut chip thickness is comparable to the cutting edge radius in micro cutting. Material flow is limited by the cutting edge round. The effective rake angle γ_e is negative, as shown in Fig. 5. It means that the micro cutting process actually is a negative rake angle cutting. And the negative rake angle magnitude is related with a_o/r_n. Consequently, the influence of a_o/r_n on micro cutting process can be reflected by the negative effective rake angle. Previously Komanduri [19] conducted nanometric cutting simulation on copper with sharp tools of different negative rake angles. They found that the specific cutting energy rises with decrease in negative rake angle.

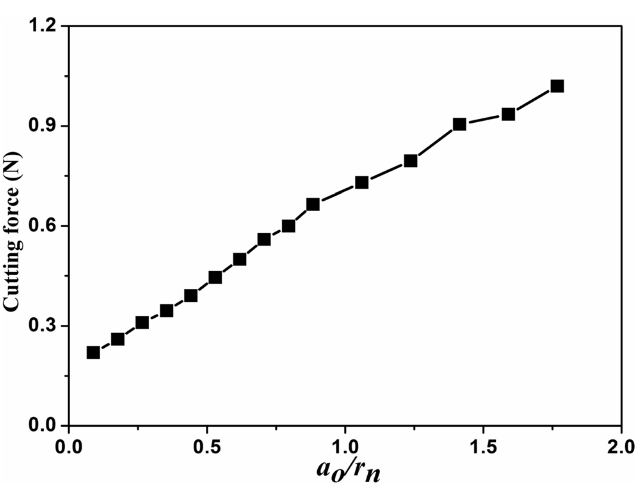


Fig. 3 The cutting force variation

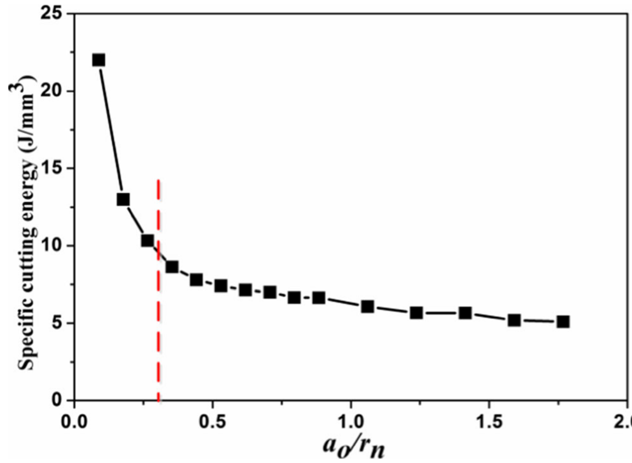


Fig. 4 The specific cutting energy variation

In general, when uncut chip thickness is less than cutting edge radius, the equivalent rake angle γ_e of a given point can be considered as shown in Fig. 5. Based on [20], it can be expressed as the following formula:

$$\gamma_e = -\sin^{-1}\left(1 - \frac{a_0}{r_n}\right) \tag{3}$$

where a_0 is the uncut chip thickness, r_n is the cutting edge radius. This equivalent rake angle often is regarded as the rake angle of given uncut chip thickness and cutting edge radius [20, 21]. We call this calculation is the tangent method. The calculated effective negative rake angle versus a_o/r_n by the tangent method is shown in Fig. 6. This method only considers the equivalent rake angle of the intersection point of

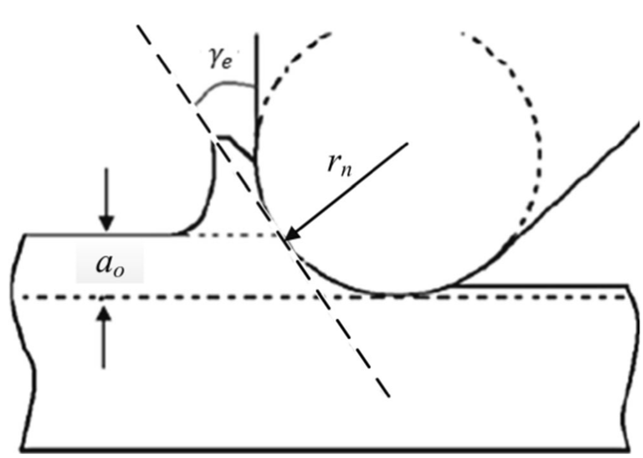


Fig. 5 The effective negative rake angle in micro cutting

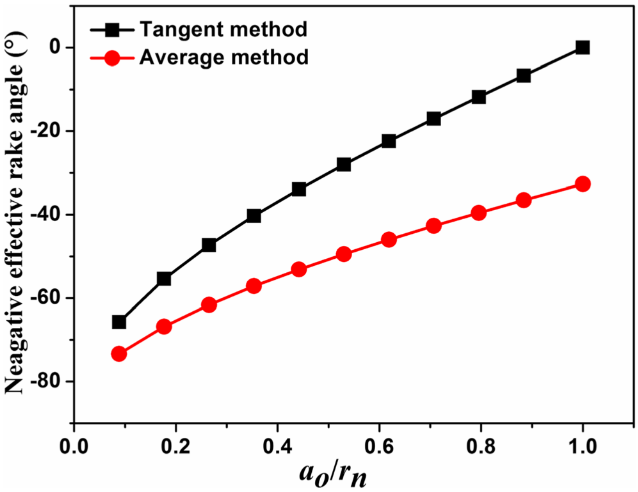


Fig. 6 The negative effective rake angle versus a_o/r_n

the uncut workpiece surface and the cutting edge arc, without taking in account all of the cutting part under the intersection point. So this method underestimates the real negative effective rake angle actually. As an example, when a_o/r_n=1, the effective rake angle-based Formula (3) is zero. But in fact, the workpiece material is cut by the bottom half arc of the cutting edge round. So the real effective rake angle should be negative.

To calculate the real effective rake angle, a new calculation model is developed. The average value of equivalent rake angles of all the cutting part points is considered as the real negative effective rake angle. We call it the average method. It can be calculated by the averaging of equivalent rake angle calculated by tangent method between zero and a_o/r_n. First, the equivalent rake angle is calculated based on the tangent method, as shown in Fig. 6. Later integration is carried on Formula (3) from zero to the given a_o/r_n. Last, the integration value is divided by the a_o/r_n. This calculated result is regarded as the real negative effective rake angle γ_r of a specify a_o/r_n. It can be formulated as:

$$\gamma_r = \left[\left(1-\frac{a_0}{r_n}\right) \times \sin^{-1}\left(1-\frac{a_0}{r_n}\right) + \sqrt{1-\left(1-\frac{a_0}{r_n}\right)^2} - \frac{\pi}{2}\right] / \frac{a_0}{r_n} \tag{4}$$

where a_0 is the uncut chip thickness and r_n is the cutting edge radius. The variation of real negative effective rake angle with aspect to the ratio of a_o/r_n is shown in Fig. 6. From the results, the effective rake angle is found to be more negative with the reduction of a_o/r_n. When a_o/r_n=0.09, the negative effective rake angle is as large as −74°. Even with the ratio of a_o/r_n= 1, there is a negative rake angle of −33°. It can be known that micro cutting is a cutting process of large negative rake angle.

When cutting is performed with large negative rake angle tool, the flow of the material front of the tool face is said to be in two directions, some under the flank face and some up the rake face to form a chip, with a stagnation point, as shown in Fig. 7. There is no chip formation if the rake angle is negative enough. Komanduri [22] performed orthogonal cutting on mild steel with negative rake angle tool, they found that chip formed for all rake angles down to −75°. Their nanometric cutting simulation on copper showed that no chip is formed when the tool rake angle is more negative than 65° [19]. Lai [20] also pointed out that the critical negative rake angle for chip formation of copper is between −60° and −65° from sharp tool cutting in MD simulation. From the effective rake angle curve, it can be calculated that when the effective rake angle is −60°, the ratio of a_o/r_n is about 0.2. When the effective rake angle is −65°, the ratio of a_o/r_n is 0.3. It means the minimum chip thickness of copper is about 0.2–0.3 times of the cutting edge radius size.

Figure 8 shows the specific cutting energy in dependence of the negative effective rake angle and the ratio of a_o/r_n. When the effective rake angle does not reach the critical negative rake angle, the specific energy gradually increases with the decrease of a_o/r_n. With further reduction of a_o/r_n, the effective rake angle decreases to less than the critical negative rake angle. The tool just plows over the workpiece surface and no chip is formed. The specific energy sharply increases with the reduction of a_o/r_n.

3.2 Surface quality

Surface quality is very important due to its significant influence on the mechanical and physical performance of micro parts. Surface roughness usually is considered as the indicative parameter of the surface quality. The surface roughness is mainly affected by the feed rate and tool nose radius in conventional turning. The theoretical residual surface is shown in Fig. 9a. The theoretical surface roughness schematic is shown in Fig. 9b. Based on [18, 23], R_z can be formulated as:

$$R_z = r - \sqrt{r^2 - \left(\frac{f_r}{2}\right)^2} \tag{5}$$

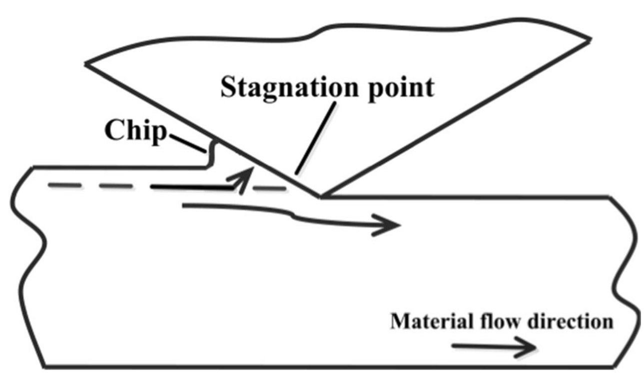


Fig. 7 Material flow in large negative rake angle cutting

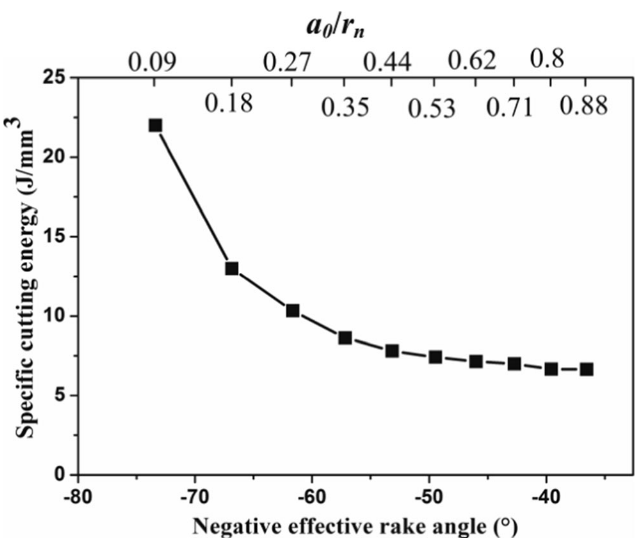


Fig. 8 The specific cutting energy versus effective rake angle

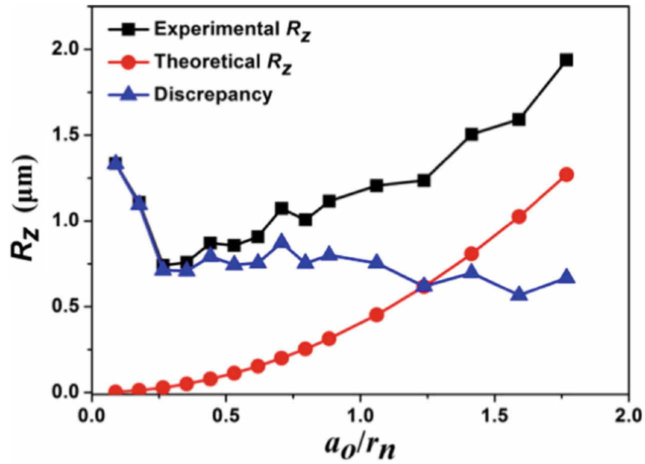
where r is the tool nose radius and f_r is the feed per turning. Based on the profile arithmetic average error standard formula [24]:

$$R_a = \frac{1}{n}\sum_{i=1}^{n}|y_i| \tag{6}$$

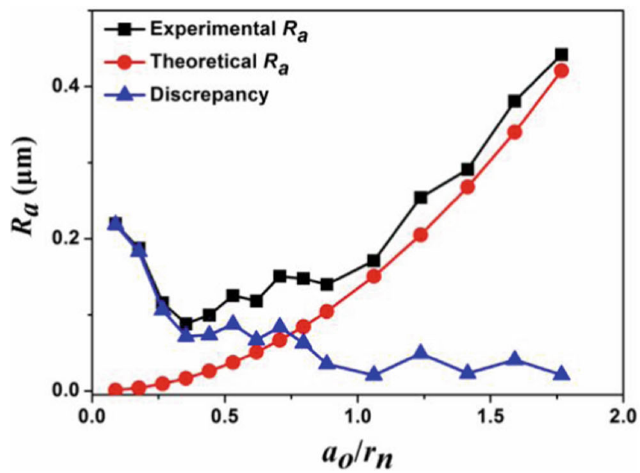
The theoretical surface roughness R_a can be calculated as:

$$R_a = r - 0.5 \times \sqrt{r^2 - \left(\frac{f_r}{2}\right)^2 - \frac{r^2}{f_r} \times \sin^{-1}\left(\frac{f_r}{2r}\right)} \tag{7}$$

The comparison of experimental surface roughness against the ratio of a_o/r_n with the theoretical value is shown in Fig. 10. The theoretical surface roughness is observed to always decrease with the reduction of a_o/r_n. However, the experimental surface roughness is found to decrease at first, reach a minimum value, and then increase with the further decrease of a_o/r_n. The minimum R_z obtained at the ratio of 0.27 is 0.741 μm and the minimum R_a achieved with the ratio of 0.35 is 0.088 μm. There is always a positive discrepancy between the experiment surface roughness and the theoretical value. It is interesting that the discrepancy also nonlinearly increases



(a) R_z variation with a_0/r_n

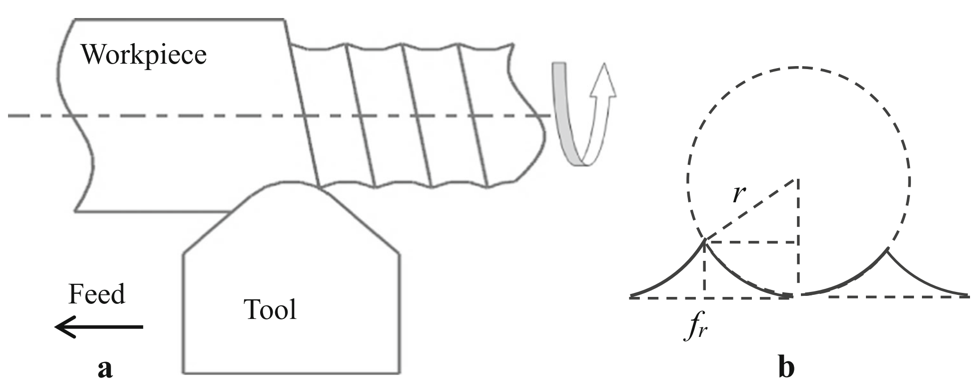


(b) R_a variation with a_0/r_n

Fig. 10 The surface roughness variation with a_0/r_n. (**a**) R_z variation with a_0/r_n. (**b**) R_a variation with a_0/r_n

with the reduction of ratio. In micro cutting, the workpiece and tool contact area is small, and there is a high pressure act on the material around the cutting edge round. The machined surface side material is extruded to plastic side flow. This leads to the experimental peak to valley height being larger than the theoretical result. If the pressure is higher, more material will

Fig. 9 The residual surface of turning



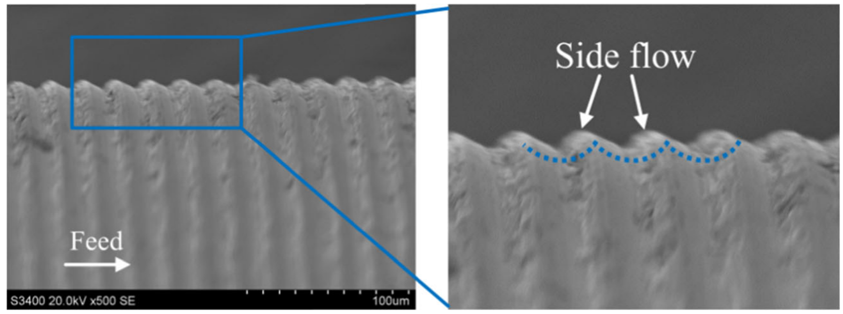


Fig. 11 The surface morphology (a_0/r_n=1.41)

have plastic side flow and the peak to valley also will rise. From the specific cutting energy results it can be known that the unit pressure nonlinearly increases with decrease of a_o/r_n. It results in the plastic side flow also nonlinearly rising. The discrepancy curve is similar to the specific cutting energy curve.

The machined surface morphology observed by the SEM is shown in Fig. 11. The dotted line represents the theoretical residual contour. The plastic side flow can be clearly seen in the picture. At the beginning, few side flows occur and have little effect on the surface roughness. With decrease of the ratio, more side flows happen. The discrepancy between the real surface roughness and the theoretical value increases. But the surface roughness still is decreasing. With further reduction, the effective rake angle is more negative than the critical negative rake angle. The tool just plows over the workpiece surface and no chip formation. The surface roughness begins to rapidly rise. The minimum surface roughness is achieved near the minimum chip thickness.

3.3 Chip formation

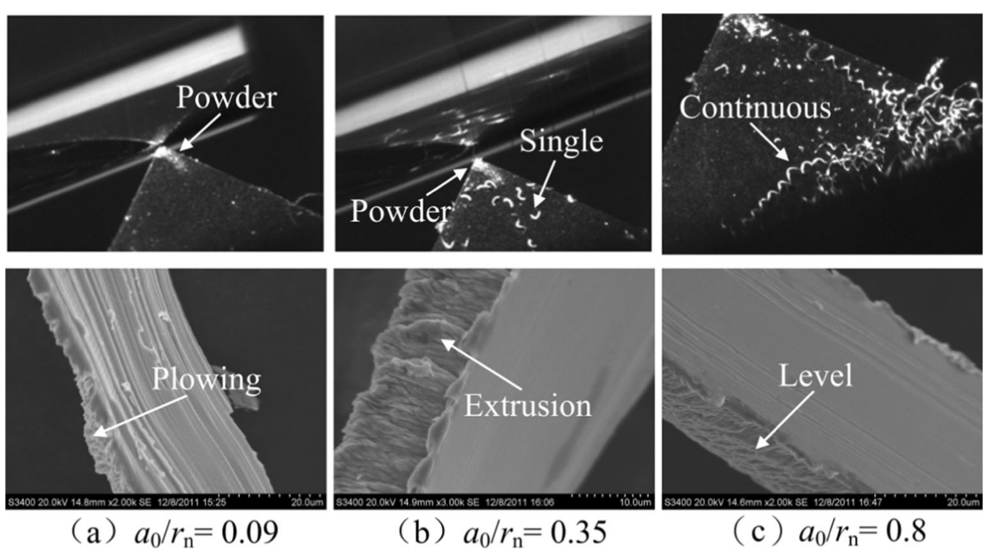
The chip morphology is observed by both microscope and SEM, as shown in Fig. 12. At beginning, the chip topography is continuous and naturally curl. The SEM picture shows the chip side surface has little extrusion. When the ratio decreases to near the minimum chip ratio, the chip formation is not stable. Some chips are small single circular arc-shaped, some are powder-shaped. A lot of materials are extruded to the side face which makes it look very rugged. With further decrease, the effective rake angle is more negative than critical negative rake angle. The continuous chip formation is really hard. All the chips are fine powder-shaped. There are severely plowing marks on the chip surface. The chip side face is completely plowed to flat. It indicated the intense plowing by the cutting edge round.

4 Summary and conclusions

This paper presents an experimental investigation of specific cutting energy and surface quality based on the negative effective rake angle in micro turning with PCD micro tool. The following conclusions have been drawn:

- Micro cutting is a large negative rake angle cutting process. A new model is developed to calculate the negative effective rake angle in micro cutting. The effective rake

Fig. 12 Chip morphology



angle is found to be more negative with the decrease of a_o/r_n. The minimum chip thickness is calculated to be about 0.2–0.3 times of the cutting edge radius based on the critical negative rake angle.

- When the effective rake angle does not reach the critical negative rake angle, the specific energy gradually increases with the decrease of a_o/r_n. With further reduction, the effective rake angle decreases to more negative than the critical rake angle. The tool just plows over the workpiece surface and no chip formation. The specific energy increases sharply.
- Plastic side flow leads to the real surface roughness being larger than the theoretical value. The surface roughness decreases with reduction of a_o/r_n at first. As the effective rake angle reaches the critical negative rake angle, chip formation is very unstable. The surface roughness begins to rise rapidly. The minimum surface roughness is achieved near the minimum chip thickness.

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