DOI: 10.1007/s12541-013-0048-4

Size Effect on Surface Roughness in Micro Turning

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KEYWORDS: Surface roughness, Peak-to-valley height, Micro turning, Size effect, Side flow

The conventional model predicts that the surface roughness decreases with feed and fits well with the measured results, even in the micro turning process. But it is observed that surface roughness increases with feed decreases when the feed is in the range of micro scale. Based on the analysis of peak-to-valley formation process, a quadratic prediction model, which divides the height of peak-to-valley into two parts: one part is piled in front of the rake face while the other is piled on the flank face and is more accurate, is established considering the effect of tool geometry, cutting parameters and pile-up of work piece. The prediction model is calibrated and verified via two groups of micro turning experiments. Results show that size effect of specific cutting energy increases the surface roughness at small feeds. The difference between the theoretical and measured results at small feeds is mainly induced by the pile-up of work piece material around the rear face. The best surface roughness can be obtained when the feed per revolution equals 0.1 time of the cutting edge radius.

Manuscript received: December 11, 2011 / Accepted: November 20, 2012

1. Introduction

Surface quality is an important character of micro optics and mold parts. Surface roughness is predominantly considered as the most important feature of practical engineering surface due to its crucial influence on the mechanical and physical properties of a machined part.[1,2] Surface roughness can affect the tribological performance of micro parts. Micro cutting, such as micro turning and micro milling, is the main technology to manufacture micro parts. Predict the surface roughness of micro parts machined surface through a mechanical model can improve the quality and performance of micro parts. Under given cutting conditions, prediction of surface roughness resulting from metal removal operations is one of the major goals in the machining area.

Conventional surface roughness models have assumed that geometric surface finish in single-point turning is influenced by feed per revolution and cutting edge radius.[3,4] On the other hand, it is suggested that the surface roughness is additionally affected by depth of cut, tool wear, workpiece hardness, spindle speed, etc.[5,6] It is obvious from Fig. 1 that the peak-to-valley height is a function of feed per revolution and cutting edge radius.[3] The peak-to-valley height considering the feed per revolution and cutting edge radius can be used to calculate the surface roughness as shown in Eq. 1.[6]

$$R_{th} = \frac{f^2}{8r} \tag{1}$$

where R_{th} is the theory value of the peak-to-height, f is the feed per revolution, and r is the cutting edge radius.

Shaw[3] has pointed out that the stranded area will be plastically deformed and side flow takes place. Consequently, it is not likely to completely account for the observed trend at small feeds. Shaw[3] even thought that the material plastic side flow is the most significant factor for the surface roughness increasing at small feeds due to size effect of specific cutting energy. In micro cutting, the cutting edge radius and the uncut chip thickness are in the same range of micrometer and the ratio of uncut chip thickness to cutting edge radius results in size effect of specific cutting energy.[7] Liu[8] explained that size effect on the surface roughness is due to the forward plastic side flow according to the gradient theory at micron-meter feed rates. This paper attempts to explain surface roughness increases at small feeds due to the size effect of specific cutting energy in micro turning. In addition, the surface roughness associated with work piece side flow is modeled and analyzed quantitatively.

2. Mechanism of size effect on the roughness

Aramcharoen[9] found that the surface roughness of bottom plane increases when the feed per tooth is smaller than the cutting edge radius. In micro cutting, the dotted curve lines show (see Fig. 2) that

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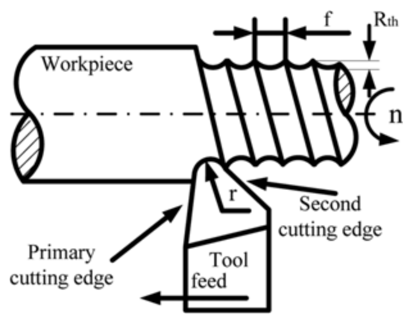

Fig. 1 Diagrammatic sketch of cutting operation showing primary and secondary cutting edges and characteristic waveform left on the finished surface[3]

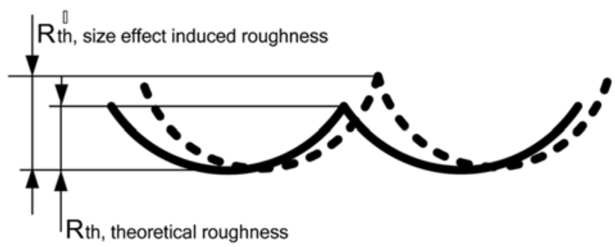

Fig. 2 Surface roughness profile generated by tool with radius with and without size effect

the material in front of the primary cutting edge is piled, while the material around the second cutting edge flows back due to the high normal pressure. It is obvious that the value of the peak-to-valley height is larger than the theoretical result considering the side flow (see Fig. 2). The height of material piled around the cutting edge is dependent on the strength and ductility of the workpiece,[10] the geometry of the tool cutting edge[11] and the surface topography of the stranded layer. It is possibly that there is an increasing trend in surface roughness at low feeds, which is due to the size effect in micro turning. It is well known that the size effect of specific cutting energy shows unit pressure increases with the ratio of uncut chip thickness to the cutting edge radius decreasing in micro cutting.[7] If the workpiece around the cutting edge is under higher pressure, more side flow will occur and the peak-to-valley height will rise. Consequently the peak-to-valley height will be measured and the prediction of surface roughness is modeled and validated through micro turning experiments.

The surface roughness prediction model is based on the scratch identification test. The scratch test is used mainly to study the mechanical properties of materials near the indenter surface. The scratch hardness and surface deformation depend in particular on the yield stress of the material, the interaction of the contact face and the indenter geometry.[12]

The micro turning is similar to the scratch test in the feeding direction. The material will flow to the minimum resistance direction when the pressure reaches $0.57\sigma_y$, where σ_y is the yield strength of the material.[13] The rheological coefficient x[14,15] represents the flow ability of work piece with Eq. (2).

$$x = \frac{E}{\sigma_y \tan \alpha} \tag{2}$$

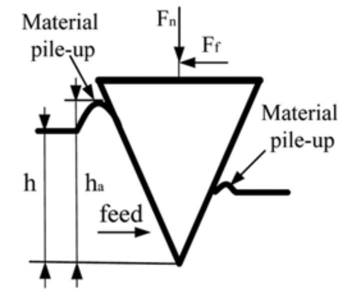

Fig. 3 Sketch of contact depth and pile-up height in scratch

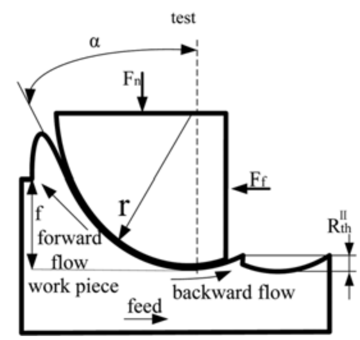

Fig. 4 Side flow around the cutting edge in micro turning

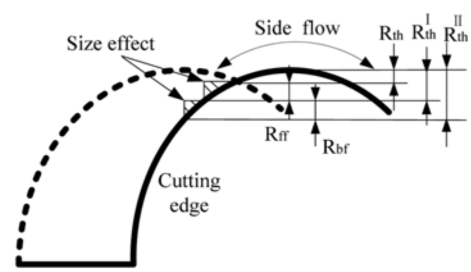

Fig. 5 Sketch of pile-up surface roughness

where E is the Young's modulus of workpiece, α is the actual semi-apical angle of the indenter according to the geometry of the cutting edge, $\alpha = \arcsin(1 - t/r)$ and σ_y is the yield stress of the workpiece.

The rheological coefficient x is an important parameter to evaluate the pile-up height. It can be used to calculate the height R_{th}^{II}(see Fig. 3). Bucaille[15] showed that the pile-up height in scratch tests is dependent on the rheological coefficient x with Eq. (3).

$$\frac{h_a}{h} = 0.3084 \ \ln x + 0.3233 \tag{3}$$

where h_a is the depth from the bottom of the scratch groove to the top of pile-up (see Fig. 3), h is the contact depth.

According to similarity principle, the material pile-up process in the feeding direction in micro turning is similar to the scratch test with a round indenter.[16] The pile-up height consists of two processes in the feeding direction of micro turning. First, the material piles in front of the primary cutting edge, then the material flows along the rear face and piles up (see Fig. 4). The pile-up height can be divided into two (see Fig. 5) components; R_{ff} is the forward side flow pile-up height, while R_{bf} is the backward side flow pile-up height. On the basis form of Eq. (3), the peak-to-valley height due to side flow can be given in Eqs. (4) & (5).

Table 1 Factor and factor levels for R_{th}^{II} model calibration tests

Feed (μm/r)	40 50 75 90 115 160 240
Depth of cut (μm)	100
Speed (m/min)	110

$$\frac{R_{th}^{I}}{R_{th}} = k_1 \ln x + k_2 \quad (4)$$

$$\frac{R_{th}^{II}}{R_{th}^{I}} = k_3 \ln x + k_4 \quad (5)$$

where k_i is the fitting coefficients, i is from 1 to 4.

Merging Eqs. (4) & (5), the relationship between R_{th}^{II} and R_{th} can be expressed with Eq. (6)

$$\frac{R_{th}^{II}}{R_{th}} = k_1 k_3 \ln^2 x + (k_1 k_4 + k_2 k_3)\ln x + k_2 k_4 \quad (6)$$

Eq. (6) can be simplified as Eq. (7)

$$\frac{R_{th}^{II}}{R_{th}} = g_1 \ln^2 x + g_2 \ln x + g_3 \quad (7)$$

The coefficients g_i can be calibrated via micro turning tests performed over a wide range of cutting conditions.

3. Experimental procedure

The objective of the calibration experiments is to establish a quantitative relationship between the peak-to-valley surface roughness induced by size effect of the specific cutting energy and the rheological coefficient x. This is related to the determination of the constants g_1, g_2 and g_3 in Eq. (7). Further, the surface roughness is linked to the cutting parameters.

Micro turning tests were conducted on a CA6140 lathe. Workpiece used for turning process was AISI1045 with 50 mm initial diameter bar. Ceramic tools (TNGA160408T01020) of KENNAMETAL with 796.27 μm nose radius (standard deviation 6.91 μm) and tool holder MTGN R 2020K16 were used for experiments. The insert gives a nominal rake angle of 0° so that the feeding direction can be regarded as an orthogonal cutting. The cutting parameters were listed in Table 1.

The following factors were recorded in the experiments: material pile-up height, cutting force, depth of cut and different feeds. The material peak-to-valley height is measured with the VHX-600 ESO Digital Camera of KEYENCE Company. The cutting forces can be got from the cutting force dynamometer or the model.[17,18]

4. Results and discussion

Eq. (7) is fit to the data in Table 2 (see Fig. 6) and the coefficients g_i are obtained. It can be seen that the coefficients fit well with the scattered points in the Fig. 6, with $R^2 = 0.995$. The peak-to-valley roughness R_{th}^{II} induced by plastic side flow can now be established as a function of the material pile-up through Eq. (8)

Table 2 Predicted rheological coefficient in micro turning

Rheological coefficient	R_{th}^{II}/R_{th}
241.6	14.80
324.8	8.96
463.5	3.87
526.0	3.24
617.0	2.71
767.9	1.75
1060.0	1.07

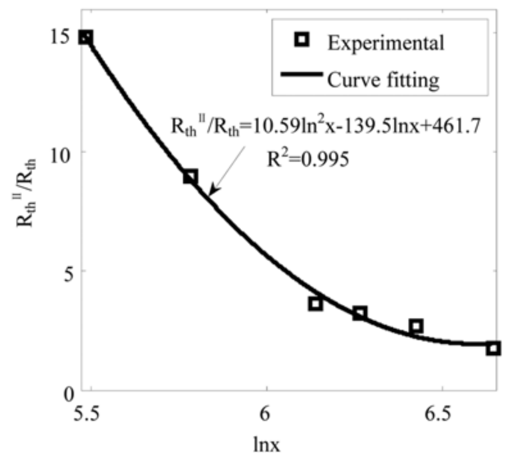

Fig. 6 Curve fitting of coefficients g_i

Table 3 Factor and factor levels for R_{th}^{II} model validation tests

Feed (μm/r)	40 60 80 100 120 160 200 300
Depth of cut (μm)	100
speed (m/min)	110

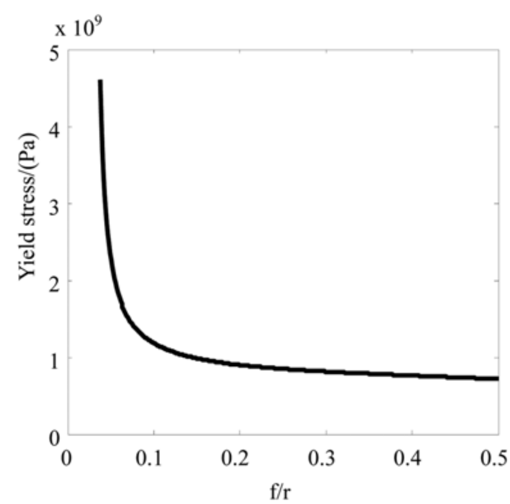

Fig. 7 Yield stress around the primary cutting edge

$$R_{th}^{II} = (g_1 \ln^2 x + g_2 \ln x + g_3)R_{th} \quad (8)$$

where g_i can be obtained from micro turning experiments.

Micro turning tests for surface roughness model validation were conducted at different feeds ranging from 40 to 300 μm. The cutting parameters used in validation tests are listed in Table 3. The yield stress of the work piece around the rake face is plotted in the Fig. 7. It is

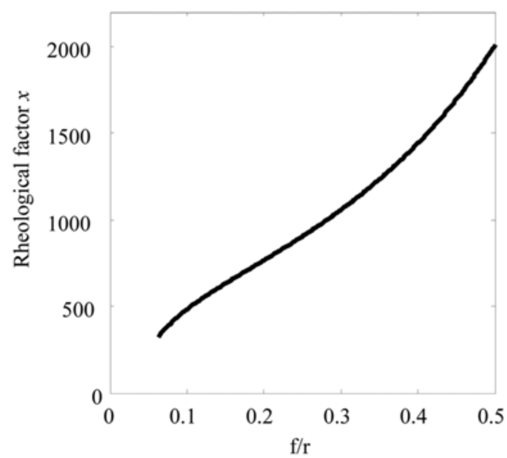

Fig. 8 The rheological coefficient of rake face

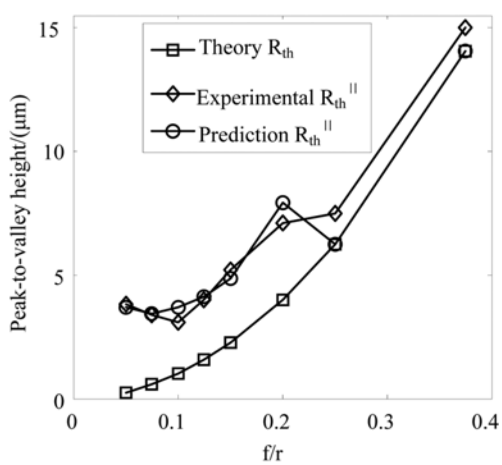

Fig. 9 Fitting model of surface roughness

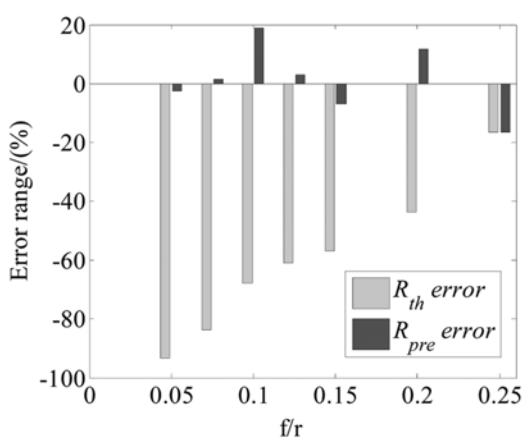

Fig. 10 Error bar of R_{th} and R_{pre}

Table 4 Predicted versus measured surface roughness in micro turning (μm)

f/r	R_{exp}	R_{th}	R_{th} error (%)	R_{pre}	R_{pre} error (%)
0.05	3.8	0.25	-93.4	3.70	-2.6
0.075	3.4	0.56	-83.5	3.44	1.3
0.10	3.1	1.00	-67.7	3.70	18.8
0.125	4.0	1.56	-60.9	4.10	3.0
0.15	5.2	2.25	-56.7	4.80	-7.0
0.20	7.1	4.00	-43.7	7.90	11.7
0.25	7.5	6.25	-16.7	6.25	-16.7

shown that the yield stress increases with the ratio of feed per revolution to cutting edge radius decreases. The intensive yield stress increases the flow ability of the workpiece, and the pile-up forms easily when the ratio of feed per revolution to cutting edge radius decreases. Fig. 8 shows the trend of the rheological coefficient varies with the ratio of feed per revolution to cutting edge radius according to Eq. (2). As Bucaille[15] has summed that the pile-up height in front of the indenter decreases with the rheological coefficient decreases, while the height behind of the indenter increases with the rheological coefficient decreases. The pile-up height of rear face increases with the ratio of feed per revolution to cutting edge radius decreases in micro turning, and it is not ignorable in the surface roughness calculation model.

The surface roughness predicted results are compared with the experiments results in micro turning as shown in Fig. 9 and Table 4. The errors are compared in the Fig. 10 and Table 4, the R_{th} error increases with *f/r* decreases and even reaches 93.4%, while the R_{pre} error is stable and in the range of 20%. If the ratio of feed per revolution to cutting edge radius *f/r* is smaller than 0.2, the pile-up of work piece will have great effect on the surface roughness. The value of surface roughness decreases with the ratio of feed per revolution to cutting edge radius *f/r* decreases and the height reaches the minimum when the ratio *f/r* reaches 0.1. If the feed continues to decrease, the results will increase due to the pile-up height around the cutting edge and the conventional model R_{th} fails to predict the experimental results. The developed model R_{th}^{II} fits well with the experimental results. This is because the strong size effect of specific energy extrudes the material.

5. Conclusion

An accurate prediction model of surface roughness is established in this paper. This approach is based on considering the effect of pile-up formation process, tool geometry and cutting parameters. The conclusions can be summarized as follows:

1. The peak-to-valley height of surface roughness increases when the ratio of feed per revolution to cutting edge radius is smaller than 0.1 due to the side flow induced by the size effect of specific cutting energy.
2. The best surface roughness can be obtained when the ratio of feed to cutting edge radius reaches 0.1 in micro turning.
3. According to the analysis of pile-up height formation process, a quadratic prediction model of surface roughness is achieved. The prediction model fits well with the experiment results and the percentage error is less than 20% for all the results.

ACKNOWLEDGEMENT

This work has been supported by the National Basic Research Program of China (2009CB724401), National Natural Science Foundation of China (50935003), and Foundation of Shandong Province of China for Distinguished Young Scholars (JQ200918), Mega-project of High-grade NC Machine Tools and Basic Manufacturing Equipment (2011ZX04016-031).

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