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Exit burr and break off analysis in micro grooving pyramid pattern

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Abstract

Burr formation in micro cutting always causes serious problem in precision engineering. It affects badly on product's quality, especially the finishing surface. Besides, deburring techniques on micro cutting are almost impossible or too complicated and high-cost. Understanding burr formation phenomenon and minimizing burr size in correlation with cutting conditions and material properties, in this case, are more appropriate. Many of previous researches about burr formation are successful and well adapted in enhancing quality and productivity of manufacturing industry. But most of them are related to general cutting, so micro burr problems are still not enough to serve the industry. For the purpose of exploring the burr phenomenon in micro metal cutting, the burr happens at the exit edge of the pattern, in the cutting direction - exit burr - of pyramid pattern is introduced in the paper. Besides, the exit break off which occurs during the exit burr formation is also studied. The analytical solutions for predicting the burr and break off size in each case are also proposed and compared with experiments.

Keywords: Burr formation, Micro grooving, Micro pattern, Slip line theory, Hardness.

1. Introduction

The motivation for micro manufacturing arises from the translation of the knowledge obtained from the macro-machining domain to micro-domain. However, there are challenges and limitations on micro-machining, and simple scaling might not be used to model the phenomena of micro machining operations effectively [1]. High-accuracy miniaturized components are increasingly in demand for various industries, such as aerospace, biomedical, electronics, environmental, communications, and automotive. This miniaturization will provide micro systems that promise to enhance health care, quality of life and economic growth in such applications as micro channels for lab-on-chips, shape memory alloy 'stent', fluid graphite channels for fuel cell applications, sub-miniature actuators and sensors, and medical devices [2-5].

One of the most popular micro manufacturing methods is micro cutting, especially metal cutting. And micro patterns which are applied in most of the application listed above are fabricated by micro grooving. Burr formation in micro grooving usually ruins the finishing pattern surface. Deburring techniques on those surfaces are almost impossible or too specific, complicated and high-cost [6]. Understanding burr formation phenomenon and minimizing burr size in correlation with cutting conditions and material properties, in this case, are more appropriate [7]. But most of previous successful researches are about burr formation in general cutting, so micro burr problems still need to be solved in order to serve the requirement of the industry. For the purpose of exploring the burr phenomenon in micro metal cutting, two cases of burr formation in turning micro patterns are introduced in the paper. The burr happens along the cutting direction - side burr - of prism pattern, and the one happens at the exit edge of the pattern, in the cutting direction - exit burr - of pyramid pattern.

2. Exit burr and break off in grooving micro pyramid pattern

2.1. Cutting model

Pyramid pattern can be formed in the sequence of first groove to create prism pattern and the second groove which is orthogonal with the first one. During the second groove each time when tool moves across one prism pattern, there is exit burr or break-off at the edge as shown in Fig. 1. In this case, rake angle is zero so that exit burr happens in orthogonal cutting. Taking a cross section in the pattern as Fig. 2 allows exploring the cutting process and exit burr phenomenon.

Exit burr mechanism can be divided into 3 parts based on the observation from the machining tests on plasticine [8]. Initiation: as the tool approaches the end of the workpiece, there is a transition point at which the chip formation stops and plastic deformation below the machined surface in the cutting direction begins. Initiation of burr formation is characterized by the initial negative shear angle β_0, and initial distance of tool tip ω. An interesting point is that the

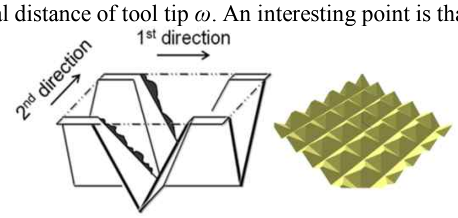

Fig. 1 Pyramid model

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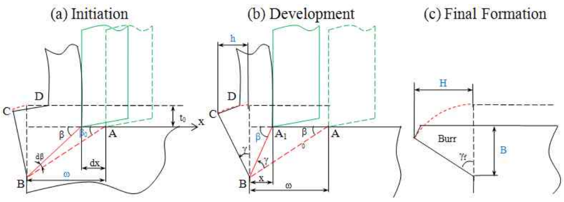


Fig. 2 Exit burr formation

initial negative shear angle, β_0, is almost 20^0 regardless of the workpiece material and the cutting conditions, when exit angle is 90^0. This has been verified by previous researchers [8,9]. Development: as the tool move forward after initiation from A to A_1, negative shear plane also rotates from BA to BA_1. Once the initial negative shear plane is formed, the final point of the negative shear plane which crosses the exit surface of the prism pattern at point B in Fig. 2, will act as plastic hinge and not translate during the burr development. Formation: finally the burr is formed with or without fracture because of increasing strain along the negative shear plane as the tool approaching the end of workpiece. If fracture occurs along the negative shear plane or through existing burr, it will remove or reduce the burr.

2.2. Exit burr formation without break off

In the first stage of studying the exit burr of micro pyramid pattern, it is recommended to apply the model about exit burr in general cutting model of [9] following the cutting schedule of the second groove. At each depth initial length is also assumed as burr thickness and can be obtained as

$$\omega = \frac{k_s\left(d_c\dfrac{1}{\sin\phi} + sL\sin\phi\right)}{\cos\phi\left(\dfrac{k_0}{2}\cos^2\beta_0 + \dfrac{S_y}{4}\tan\beta_0\right)} \quad (1)$$

with k_0 is the yield shear strain obtained by Mise criterion, k_s is shear yield strength in shear zone, L is tool chip contact length.

And burr size can be obtained geometrically from Fig. 2 by

$$B = \omega\tan\beta_0 \quad (2)$$

$$H = \left(d_c + B\right)\sin\gamma_f \quad (3)$$

which B, H are burr thickness and burr height, respectively.

2.3. Exit break off during burr formation

Beside the burr development, edge break-off during burr formation greatly affects the product quality. If edge breakout occurs instead of burr formation, a crack along the negative shear plane will be initiated. It depends on the material behavior, particularly the fracture strain in this case. A fracture criterion is necessary for predicting the occurrence of fracture during burr formation. While the criteria for initial yielding and brittle fracture require only the current state of stress, the behavior of a ductile material is not clearly defined due to the extent of the plastic deformation that can occur before fracture happens: the behavior depends on the deformation history in the ductile material. The behavior of most materials is practically located between two extreme cases: a fully ductile material

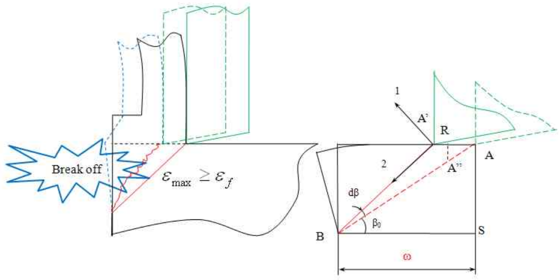


Fig. 3 Exit Break off model

and a perfectly brittle material which fracture without plastic deformation, like crystal. In a ductile material such as copper which large plastic deformation occurs before fracture, it is not convenient to decide the fracture condition by using stress state of the workpiece. It is better to use strain instead of stress to apply with the fracture criterion. Even in coated copper, a less ductile material which is accompanied by less plastic deformation before fracture, the ductile fracture criterion by McClintock is assumed to be applied. Applying McClintock's criterion, Ko's work [9] shows that with pure copper using strain hardening index 0.54 gives fracture strain in exit burr formation $\varepsilon_f = 2.11$. And according to the work of Lin [10] the fracture strain ε_f of copper alloy is 1.2. So it's suitable for applying fracture strain $\varepsilon_f = 1.2$ in this study. The strain at the initial point is zero and increases almost linearly as the negative shear angle increases. So by monitoring the maximum shear strain of the area under grooved surface, fracture can be detected. If the maximum strain is greater than the fracture strain then fracture happens.

$$\varepsilon_{\max} \geq \varepsilon_f \quad (4)$$

The maximum shear strain, ε_{max}, here can be approximated

as the strain at the tool tip in Fig. 3. And it can be obtained as

$$\bar{\varepsilon}_{tooltip} = \varepsilon_{\max} = \int_{\beta_0}^{\beta}\left(\frac{\sqrt{2}}{3}\sqrt{\frac{6}{\beta^2} + \frac{3}{2\tan^4\beta}}\right)d\beta \quad (5)$$

3. Experiment and results

Roll mold is coated with copper and grooved on a precise turning center, as shown in Fig. 4, with SCD V shape 60^0, 80^0, 90^0; hardness is within the range of 210Hv to 270Hv. First groove will form prism pattern and second groove will form pyramid pattern. Test cases are also done following that sequence and captured results by SEM and optical telescope.

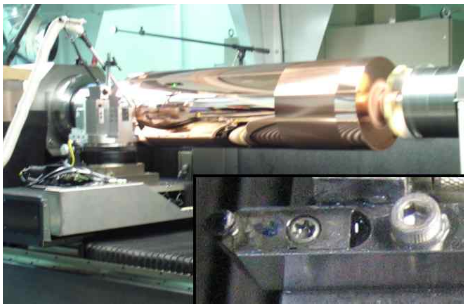


Fig. 4 Experiment setup

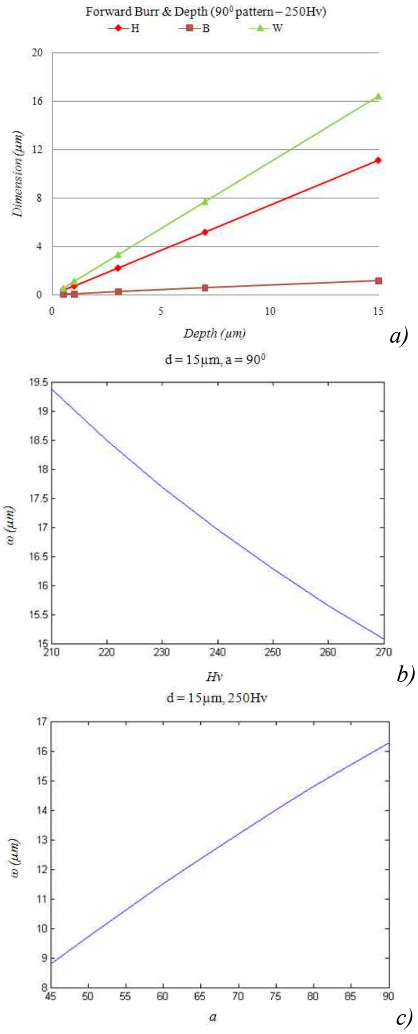


Fig. 5 Prediction results on exit burr of pyramid pattern

a) Exit burr and cutting depth, V 90^0, 250Hv

b) Initial distance and Hv

c) Initial distance and pattern angle

Some prediction results for exit burr of pyramid pattern shown in Fig. 5 conclude that exit burr size grows proportionally to the decrement of hardness and also the increment of cutting depth. In the relation with pattern angle, burr size increases when angle increase, against the rule in side burr of prism pattern. The reason comes from the geometry of the cutting model, as angle increases then cutting depth on the side wall of the pyramid increases so that burr size increases. Those predictions agree with the rules about burr formation in general cutting with previous researches [7,8,9].

By the way, in this study the main results from the experiments are about the exit break off which are also taken place during the exit burr formation. Test cases are taken with SCD V 90^0 in case of single grooving. Cutting speed for second groove is separated into two groups: high speed 300m/min with 2nd groove follows turning direction, low speed 10, 6, 5m/min with 2nd groove follows feed direction, as shown in Fig. 7. The relation of exit break off size, shape and fracture strain is predicted as Fig. 6.

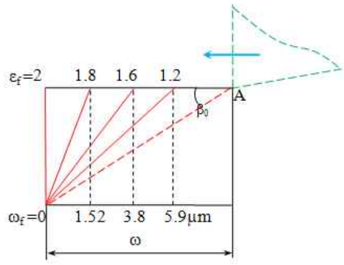
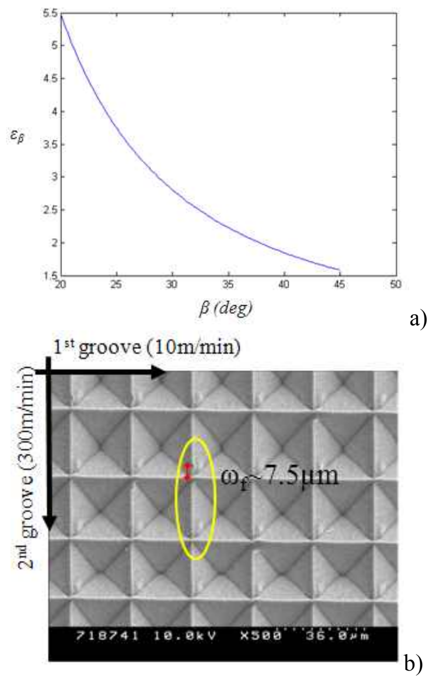
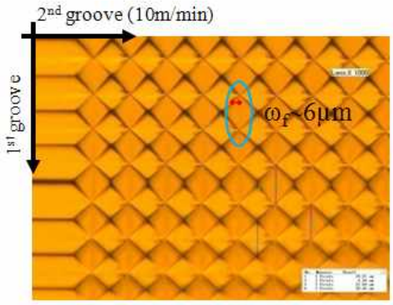


Fig. 6 Relation of exit break off and fracture strain ε_f





c)

Fig. 7 Comparison between prediction and experiment on exit break off in pyramid pattern

a) Prediction of β *till break off occur with* $\varepsilon_f = 1.2$

b) Break off size with $v_c = 300m/min$
c) Break off size with $v_c = 10m/min$

Fig. 7 shows the comparison between prediction and experiment on exit break off in grooving pyramid pattern. The predicted result for this case gives break off size 5.97μm at negative shear angle 45^0 as Fig. 7 a). The measured results from experiments with cutting speed at 300m/min and 10m/min give the break off size 7.5μm and 6μm, Fig. 7 b) and c) respectively.

4. Conclusion

Micro burr mechanism in grooving prism and pyramid pattern was investigated according to previous burr research. Taking the knowledge about burr in conventional size, macro size and several assumptions into micro pattern, a method of predicting exit burr and break off in pyramid pattern is proposed. Exit burr thickness and height can be found by Eqn. (2) and (3). But more importantly, exit break off is predicted by compare the max shear strain ε_{max} along the negative shear plane, which is found by Eqn. (5), with the fracture strain ε_f of coated copper. And the errors of predicted exit break off compared to experiments are less than 14.7%. The gap could be caused by lacking of cutting velocity effect on the burr formation model while there are several cutting speeds in the experiments.

The burr formation process is quite complex in general and macro size, and even more complicated in micro cutting. This work attempts to develop a new research field about micro burr formation in micro grooving which is widely used in nowadays industry, especially light transmission industry. Further work might worth to be carried out for the requirement of higher quality micro pattern.

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