A Study on Micro Burr Mechanism in Grooving Prism & Pyramid Pattern

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Abstract

Burr formation in micro cutting is a serious problem in precision engineering nowadays. It affects a lot on product’s quality. Besides, deburring techniques on micro cutting are almost impossible or too complicated and high-cost. Predicting and minimizing burr size in correlation with cutting conditions and controlling material properties 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 feed 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 - sideward burr - of prism pattern, and burr happens in the cutting direction - forward burr - of pyramid pattern. Then the analytical solutions for predicting the burr size in each case are also proposed.

Keywords: Burr formation, Micro grooving, Plastic deformation, 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 to 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', fluidic 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 is fabricated by micro grooving. Burr formation in micro grooving usually ruins the finished pattern surface. Deburring techniques on those surfaces are almost impossible or too specific, complicated and high-cost [6]. Predicting and minimizing burr size in correlation with cutting conditions is more appropriate [7]. But most of previous successful researches are about burr formation in general cutting, so micro burr problems still need to do many other researches in order to feed the future requirement. 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 - sideward burr - of prism pattern, and burr happens in the cutting direction - forward burr - of pyramid pattern. The research is also base on the previous work about predicting micro cutting forces [8] to go further with predicting the burr.

2. Prism pattern burr mechanism

2.1. Cutting model

The cutting model is built from a 0.2m diameter and 1m length roll mold in turning micro prism pattern. Taking a small square piece of the roll surface and assuming that is similar to groove micro prism pattern. It will make the first study about sideward burr happening along the pattern more convenient as the model in Fig. 1. Cutting material is the copper alloy (brass 6:4) coated outside the roll. Because the coating technology cannot make sure that everyplace on the roll surface could have the same coating quality, Vickers hardness tests are required to check the material properties of the surface. Taking the review of strain rate effect on ductile deformation and fracture by Rosenfield [9], only a slightly change during the tensile test seen as the strain rate is varied from static to $2.10^4$ in carbon steel, Al alloy, Ti alloy. Then combining with Akihiko’s work [10], an approximate relation between Vickers hardness and inelastic material properties could be claimed.

$$h = 2A - 2.7\sigma_y$$

(1)

With h (kg/mm²) is Vickers hardness and $\sigma_y$ (N/m²) is yield
stress of copper alloy. In micro grooving, at every cutting depth there obviously exits a critical thickness \( t_c \), which cutting is impossible. It causes plowing on the pattern’s side surface along with the formed chip removing upon it. In case of the remained thickness of workpiece reaches to \( t_c \) value, the top part of the triangle begins to deform plastically following the feed direction. This idea is led by the comparison and evaluation between burr in general cutting [11] and micro metal cutting theory [1].

To determine the critical thickness \( t_c \), the cutting of an infinite plate is considered. As shown in Fig. 2, there is uniform stress distribution along its unit width. This scheme obtained from the normal cross section of the tool edge in Fig. 1. Kazuo and Ko’s experiments [7,11] has shown that burr formation in the feed direction during turning operation is caused by the stresses in shear plane \( AD \). In this study the shear \( \tau_s \) and normal \( \sigma_n \) stresses in shear plane are considered uniform and estimated from cutting forces \( F_u \) and \( F_s \). Those forces can be estimated from \( F_u \) and \( F_s \) which are already found in previous research [8]. Due to these stresses, tension is expected in the plate when the thickness is close to \( t_c \). Slip lines AD and BC are the boundaries of the tensile area. Since the exit surface is free from external stresses, the slip lines are inclined to the exit surface at 45°, following theory of plasticity [12,13]. Besides, this theory implies that the normal and shear stresses on these lines are equal to the value of plasticity \( k \) which is determined from Tresca criterion [14] as

\[
k = \frac{\sigma_y}{2}
\]

Where \( \sigma_y \) can be obtained from Eq. (1). The force balance of element ABCD with respect to the \( x \)-axis gives

\[
\tau_s \cos \phi + \sin \phi \frac{d_s}{\sin \phi} - 4k t_c - 2k d_c = 0
\]

With \( d_s \) is undeformed chip thickness and \( \phi \) is shear angle which can be estimated using Merchant’s theory

\[
\phi = \frac{\pi}{4} + \frac{\alpha}{2} \frac{\gamma}{2}
\]

In which \( \alpha \) is rake angle, \( \gamma \) is friction angle which can be obtained by applying Merchant’s circle.

\[
\gamma = \arctan \left( \frac{F_u + F_s \tan \alpha}{F_u + F_s \tan \alpha} \right)
\]

Then from Eq. 2, \( t_c \), can be calculated

\[
t_c = \frac{d_s (\tau_s \cot \phi + \sigma_n - 2k)}{4k}
\]

or

\[
t_c = \frac{d_s \sin^2 \frac{\phi}{2} (\tau_s \cot \phi + \sigma_n - 2k)}{4k}
\]

which can be called burr thickness.

### 2.2. Sideward burr formation

Burr happens at each cutting depths of the grooving schedule, according to the cutting condition. So burr should be monitored at each cutting step and summed together to form the final burr size. But according to Fig. 3, after some depths, burr monitoring should be started from the overlapped depth at which burr is call initial burr. The overlapped depth is considered from the cutting schedule and the desired pattern as

\[
d \geq \frac{P}{2 \tan \frac{\alpha}{2}}
\]

Where \( d \) is cutting depth, \( P \) and \( \alpha \) are pitch and angle of pattern, respectively. Initial burr might develop continuously to the final depth to form final burr as Fig. 3. There should have another condition for the cutting depth that allows the initial burr keep deforming plastically or developing continuously at the next step.

\[
d \leq d^*
\]

With \( d^* \) can be obtained by doing a series of experiments. Normally the schedule of grooving a pattern is decreasing depth from the first cut to the last cut, so at any depth that satisfies condition (8), burr will start to develop till the end. This model is applied for the case on which burr is fully formed without fracture. Starting from the overlapped cutting depth the tiny thin plate material of critical thickness is shifted perpendicular to the tool edge to form the initial burr.

\[
b_0 = \frac{2r_c}{\tan \alpha}
\]

Then checking condition (8), if it satisfies then burr will develop to the end of grooving as Fig.3, otherwise it will be cut off.

\[
b_n = b_0 + \sum_{i=1}^{n} \left( d_i \sin \frac{\phi}{2} \right)
\]

which is final burr height.
2.3. Result and discussion

Fig. 4 illustrates sideward burr development through grooving schedule with several pattern angles and pitches. In Fig. 4 (a) and (b) burr height grows in different angle is not normal because of the pitch controlling the condition (7) of burr formation. But in Fig. (c) while the condition almost is satisfied the burr grows proportionally to the angle decrement and also the increment of depth [7]. Theoretically there is no burr when the pattern angle gets to 90°, but experiments show that somehow burr still happens whatever the angle is 90° or even more. This model is expected to develop more by collecting more data from experiments such as condition (8) and so on, in order to modify the algorithm to reduce the error.

3. Pyramid pattern burr mechanism

3.1. 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. In the second groove, cutting schedule is the same with the first groove so that sideward burr can happen with the overlapped depth as same as Fig. 3. Besides, during the second groove each time when tool moves across one prism pattern, there is forward burr or break-off at the edge as shown in Fig. 5. In this case, rake angle is zero so that forward burr happens in orthogonal cutting. Taking a cross section in the pattern as Fig. 6 allows exploring the cutting process and forward burr phenomenon.

Forward burr mechanism can be divided into 3 parts based on the observation from the machining tests on plasticine [15]. 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 $\beta_0$, and initial distance of tool tip $\omega$. Development: as the tool move forward after initiation from $A$ to $A_1$, $A_2$, negative shear plane also rotates from $BA$ to $BA_1$, $BA_2$. 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. 6, 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.

### 3.2. Forward burr formation without fracture

In the first stage of studying the micro forward burr, it is recommended to apply the model about forward burr in general cutting of [16] following the cutting schedule of the second groove. At each depth initial length is also assumed as burr thickness and can be obtained as

$$
\omega = \frac{k_s \left( d + \frac{1}{\sin \phi} + sL \sin \phi \right)}{\cos \phi \left( \frac{k_s}{2} \cos^2 \beta_0 + \frac{\sigma}{4} \tan \beta_0 \right)}
$$

This is applied with the yield strength, shear yield strength and strain hardening. Or obtained by

$$
\omega = \frac{F_c \left[ \cos (\phi + \gamma) + \sin \phi \sin \gamma \right]}{\cos \phi \cos \gamma \left( \frac{k_s}{2} \cos^2 \beta_0 + \frac{\sigma}{4} \tan \beta_0 \right) b}
$$

Which is implemented by vertical and horizontal cutting forces [8]. And burr height can be obtained geometrically by

$$
h = (d + \omega \tan \beta_0) \sin \gamma
$$

### 3.3. Fracture during forward burr formation

Besides the burr development, edge break-off during burr formation greatly affects the product quality. Fig. 7 illustrates two possible break-off modes of pyramid edge. If edge break-out occurs instead of burr formation, a crack along the negative deformation plane will be initiated. It depends on the material behavior, particularly the fracture strain in this case. Previous works about forward burr of Ko [16] show that even though fracture occurs during the burr formation, it does not greatly affect the burr size since the fracture usually occurs after the burr is fully formed. And plastic deformation which caused the rotation of the negative shear plane, occurred before separation. Because the large plastic deformation at the exit stage accompanies the rotation of the negative shear plane, a tensile stress will be exerted on that plane instead of a normal stress.

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 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, the fracture during burr formation could be explained using the McClintock’s ductile fracture criterion [17].

But it is not convenient when deciding 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 copper alloy, 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 [16] shows that with pure copper using strain hardening index 0.54 gives these results:

- Fracture strain $\varepsilon_f$
  - In tensile test: 2.3
  - In forward burr formation: 2.11
- Fracture negative shear angle
  - In tensile: $47.5^\circ$
  - In forward burr formation: $45^\circ$

Because of lacking experiment result of material behaviors in micro cutting it is better to assume those results for 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 strain state of the area under grooved surface, fracture can be detected. If the maximum strain is greater than the fracture strain then fracture happens.

$$
\varepsilon_{\text{max}} \geq \varepsilon_f
$$

![Fig. 6 Forward Burr Mechanism](image)

![Fig. 7 Break-off modes](image)
4. Conclusion

Micro burr mechanism in grooving prism and pyramid pattern was investigated according to previous burr research. Several assumptions are suggested for easily understanding the whole problem at the first stage of this study. This paper proposed an acceptable method of predicting the burr size particularly in grooving micro prism and pyramid patterns with copper alloy. Eq. (6) shows the critical thickness where the cutting is impossible, while (10) gives the total sideward burr height in prism and pyramid pattern. For pyramid pattern forward burr height and thickness can be obtained by Eq. (13) and (11) or (12), respectively. Besides, the method of monitoring the fracture happening during the forward burr formation is proposed together with the ductile fracture criterion of McClintock. This study is based on theoretical understanding about plastic deformation in micro metal cutting and observation of experiment results about burr in metal cutting. Certainly it should be improved at later works.

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