Burr Prediction Method in End Milling

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Abstract:
Edge imperfections are often introduced on workpieces due to plastic deformation during machining. These imperfections are known as burrs, and plastic deformation operation is the control of burr formation is a research topic of great significance for industrial applications. This study introduces a system that focuses on the prediction of burr positions and dimensions in the end milling process as a preventive measurement method. This system is based on burr formation models, analytical cutting force models, and experimental validation. Both the predicted and experimental results were found to agree in some cutting conditions.

Keywords: Burr, Prediction, Cutting force models, End milling, Cutting conditions.

1. Introduction
A burr has been defined as an excess of material beyond the edge of a workpiece as a result of the plastic deformation that occurs in cutting and shearing operations. Precision, high productivity manufacturing often requires a deburring or finishing operation. The current manual deburring method by hand is a workable solution; however, there are several limitations. It is tedious, time-consuming and produces undesirable part dimension. In particular, precautions have to be taken to ensure the safety of workers during the deburring process. In addition, there was much attention from researchers in the early 1970s to the study of burr formation and deburring techniques. Many methods have been suggested to minimize burr formation or to remove burrs. Gillespie [1] was among the first researchers to study burr formation. He points out that deburring and edge finishing on precision workpieces may constitute as much as 30 percent of the part cost. He also classifies the basic mechanism of burr formation into four basic types: Poisson burr, rollover burr, tear burr, and cut-off burr, according to the burr formation using an approximation based on the classical plastic deformation mechanism. Other researchers have studied the basic mechanism of burr formation in machining. Chern [2] and Ko [3] have given more detail of the rollover model in orthogonal and oblique cutting. Hashimura [4] and Park [5] conducted research analysis of the burr formation mechanism in orthogonal cutting, including the influence of material properties, based on a simulated analysis using the finite element method (FEM). Hashimura provided schematic views of the burr formation mechanism in different types of workpiece materials, including both ductile and brittle materials.

To date, various methods have been proposed for the development of burr prediction systems; however, there is no unique system that can be used as a preventive method and that can be applied in practical use. In this paper, a system for predicting the position and dimensions of burrs formed in the end milling process has been developed. This system is a real time NC (Numerically Controlled) machining simulation which includes a database of workpiece material properties, tool geometry, a cutting force model, cutting conditions, and a burr formation model. This information was applied for predicting the burr position and dimensions. By using the prediction system, we can optimize the factors which influence burr formation, and thus burrs can be minimized.

2. Burr formation models
In this study, two burr formation mechanisms were applied in the NC simulation system, namely the Poisson burr and rollover burr, based on entry and exit state of cutting tool. The mechanisms of orthogonal cutting and oblique cutting were also used in the system.

2.1 Review Poisson burr model
When the tool is pushed into a workpiece, the material near the cutting tool edge bulges because plastic deformation of the workpiece material around the tool occurs. In this analytical model, the cutting tool edge is considered as a cylinder with a tool radius of R. As the tool continues to advance through the workpiece, burrs are formed on all surfaces which are in contact with the tool. These burrs are called “Poisson burrs” and are the result of lateral deformation that occurs whenever a solid is compressed. They are named after Poisson’s ratio, Fig.1. The Poisson burr is relatively small in size and can be defined in terms of thickness (PBth) and height (PBh) as shown in Eq. (1) and (2) respectively.

\[
PB_{th} = R \left[ \exp(-3 \phi) \right] \left( \cos \phi \right) - 1
\]

\[
PB_{h} = \frac{d_{c}(1+\nu)\sigma_{f} \left( \exp(-3 \phi) \right) \left[ \left( \frac{-\sin \phi}{2(\sqrt{3} \cos \phi + \sin \phi)} \right) \right]}{\sqrt{3}E}
\]

Fig.1. Definition Poisson burr formation model [1].
where $w$ is the initial tool distance from the end of the workpiece and is delineated by Eq. (7) and Eq. (8) for orthogonal cutting and oblique cutting respectively. $\beta_0$ is the initial negative deformation angle and is defined by Eq. (9), $\theta_i$ is the exit angle, $a_i$ is the undeformed chip thickness, $\theta_1$ and $\theta_2$ are the rotation angles near the pivoting point on the burr side and can be defined in Eq. (10) and Eq. (11).

\[ \theta_1 = \arctan(x_i/a_i + w \tan \beta), \]
\[ \theta_2 = \arccos ((w \tan \beta \sin \chi) / x_i), \]
\[ \phi_i = \arcsin (2(k_i / \sigma) + \sin (45 - \alpha) \cos (45 - \alpha) - \sin(45 - \alpha)) / 2 \]
\[ \phi_i = \arctan (\tan \phi_i \cos i) \]

where $F_i$ is the cutting force in the cutting direction, $i$ is the friction angle obtained from $i = \arctan \mu$, $\mu$ is the coefficient of friction, $\alpha$ is the rake angle in orthogonal cutting, $\alpha_i$ is the rake angle in oblique cutting = $\arctan (\tan(\alpha_i) / \cos i)$, $d_i$ is the radial depth of cut, $k_i = \sigma_i / \sqrt{3}$ and $\sigma_i$ are shear yield stress and the ultimate tensile strength of the workpiece respectively, $\phi_i$ is the normal shear angle in oblique cutting and can be defined as in Eq. (13), $\chi = \cos i / \cos i$, $\cos(45 - \alpha) = (\cos \alpha \sin \phi_i + \sin \alpha \cos \phi_i) / \cos ? = \arctan(\sin \alpha / \tan i)$, $x_i = (0.5 \times \cos \beta_i / \alpha) i$, inclination angle $i = \pi / 2 - \alpha$.

\[ F_i = F_x \cos \alpha - F_y \sin \alpha \]
\[ P_i = \frac{F_i \times \cos \alpha - F_y \times \sin \alpha}{a_i} \]

2.2 Review rollover burr model[2-4]

This burr occurs just before the cutting tool leaves the workpiece. An elastic deformation zone appears at the workpiece edge as elastic bending and plastic deformation also appear near the primary shear zone as plastic bending. A pivoting point appears on the workpiece edge where the large deformation occurs. The burr is developed with the formation of a negative shear zone that expands from the pivoting point to the primary shear zone. Crack formation occurs at the tool tip, which leads to two types of burr at the end of deformation, a negative burr and a positive burr. The negative burr forms only for brittle materials where the crack starts at the tool tip in the primary shear zone and changes direction toward the pivoting point. These burrs are called rollover burrs, and are relatively large in size. Their size can be defined by their thickness $(RB_h)$ and height $(RB_o)$ as shown in Eq. (5) and Eq. (6) respectively.

\[ RB_h = w \times \tan \beta \]
\[ RB_o = (t_i + w \tan \beta) \times \sin(\theta_1 + \theta_2) \]
Table 1: Classification of use of burr models

<table>
<thead>
<tr>
<th>Position</th>
<th>Used burr models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exit burr</td>
<td>Exit surface</td>
</tr>
<tr>
<td>Top burr</td>
<td>Top surface</td>
</tr>
<tr>
<td>Entrance burr</td>
<td>Entrance surface</td>
</tr>
<tr>
<td>Side burr</td>
<td>Entrance surface</td>
</tr>
</tbody>
</table>

3. Burr prediction system

3.1 System architecture

The prediction system in this study consists of a PC-based NC simulator that can evaluate the state of the end milling process. The input information is the NC code which was written in form of G-code contained in a text file. The NC simulator consists of a geometric simulator and a physical simulator. The geometric simulator has all necessary information about the workpiece, tool geometry, and NC data to show the machining process. It obtains the cutting condition from updated information on the immersion angle. By judging how the movement of the cutting tool interferes with the workpiece, the immersion angle is updated and the physical simulator can instantly estimate the cutting force, which is the important piece of information in evaluating the burr size. The NC simulator predicted the burr location on a display where the burrs were shown on a workpiece model constructed from a Z-map model. The burr thickness and height were also calculated based on each position and type of the burr models applied.

3.2 Geometric simulator

Because the Z-map model is simple, it is possible to generate and update 2D arrays of Z-map constructs by the heights at the grid center (stored value) are stored in 2D arrays, Fig. 5. When the cutter moves, the interference points between the tool and the workpiece can be defined at each grid center point on the workpiece. At each interference point, the update of the Z-map model will be performed if the stored value is higher than the surface of the tool movement swept volume. The grid size can be decided freely. This has a great effect on the accuracy of the cutting condition, especially radial depth of cut which is the length of the vector $d_i$. Fig. 5. The smaller the distance the better the precision of the cutting condition but a long computation time is required. In this study, the grid size was $g = 0.05$ mm. The cutting condition, such as the axial and radial depth of cut, and the immersion angle were obtained from this model and used in a physical simulator model for estimation of the cutting forces in real time. The exit angle $\theta_{ei}$ in this study is $90^\circ$ and the tool rake angle $\alpha$ is $30^\circ$.

3.3 Physical simulator

In this simulation system, we assessed the cutting force acting on the tool rake face ($F [N]$), which can be determined by [6] Eq. (12).

$$F = \sqrt{N^2 + P^2}$$

$$F_{xy} = F \cos \alpha$$

where $N [N] = K_\alpha S$ is the normal force, $P [N] = N \tan \phi$ is the friction force acting on the rake face of the tool which occurs in the secondary shear zone. $F_{xy} [N], F_{xz} [N], F_{yz} [N], F_z [N]$ are cutting force projections on the $(x,y)$ plan, $x$-axis, $y$-axis, and $z$-axis respectively and are defined in Eq. (13) to (16), Fig. 6. Those forces become cutting forces in the cutting direction for applying in burr models base on X and Y-direction. $K_\alpha$ is the cutting constant and is determined from the combination of cutting conditions and workpiece material by experimental tests. $S$ is the total cutting area of a cutting flute and is determined by five parameters: tool radius $R$, rake angle $\alpha$, feed rate $f$, axial depth of cut $d_a$, and radial depth of cut $d_i$. These parameters were obtained from the geometry simulator and NC Code. The total cutting area was also divided into four small cutting zones within a lag angle $\psi$ to get closer to the actual cutting area. Each cutting area was calculated by cutting length $L_i$ and height $H_i$ at each segment with the rake angle, Fig. 7. The cutting lengths $L_i$ are the lengths inside the cutting areas which can be determined by cutting tool radius $R$, feed rate $f$, and radial depth of cut $d_i$ base on $\phi_i$ angle of cutting tool in the radial direction, and can be defined in Eq. (17) to Eq. (19).

$$L_{a,b} = \frac{d_i - R}{\sin \phi_i}$$

$$L_{b,c} = \frac{f \cos \phi_i - \sqrt{R^2 - f^2 \cos^2 \phi_i}}{\sin \phi_i}$$

$$L_{c,a} = \frac{d_i - f \cos \phi_i}{\cos \phi_i}$$

$\phi_i$ is the rotation or immersion angle of point a, b, c, and d.
3.4 Burr prediction module

When the interference between the cutting tool and the workpiece is found in the machining simulation, burr prediction is performed. The system determines the height of discrete points that interfere with the cutting tool, comparing them with other four discrete points. For the top burr, a comparison of the height of a discrete point between four discrete points in the direction of ±X and ±Y with the current discrete point is made, Fig. 5. If those points are higher, the system considers that a top burr has occurred. For other types of burrs, the system compares discrete point heights between four discrete points in the direction of X±1 and Y±1 with the current discrete point. In addition, the system classifies up and down milling by using the sign of vector product which forms by vector tool feed direction and vector \( d \). If the vector production has a positive sign, the system recognizes the cutting area as up milling; otherwise, as down milling. The tool geometry also has an importance effect on choosing the burr model used for the entrance burr. As in this study end mill with two flutes were used, there was a hook at the end of each tool blade of the second cutting edge. In this case, two types of burr models were used, the Poisson and the rollover burr. When interference point \( P(x_p, y_p) \) advanced to the center point \( O(x_o, y_o) \), the rollover burr was applied; otherwise the Poisson burr model was used. The effect of tool nose geometry is not considered in this study. In this study, the burr direction is based on the direction velocity of the cutting tool blades.

4. System verification
4.1 Simulation of burr formation

The proposed approach was implemented in object-oriented software under Windows using C++ Builder and the graphical library OpenGL [7]. The system showed the places where burrs occurred in different colors. The green, red, blue, yellow colors represent the top burr, exit burr (rollover burr), exit burr (Poisson burr), and side burr respectively. The tool path was also displayed in the system, showing the real size of the end mill cutting tool and workpiece, Fig.7.

4.2 Experimental verification

The workpiece materials in this study were S45C, FC250, and SUS304 steel blocks with the dimensions 40x40x50mm. The workpiece properties are shown in the table 2. In this evaluation, ten experimental tests and ten simulation tests were conducted for up and down milling. The differences between each test are shown in table 3. A VHX-600 digital microscope was used to measure average burr size. A profile measurement with a 3D composition image was employed to measure the burr height and burr thickness. The cutting fluid is not considered in this study. The comparison of predicted and experimental average burr sizes for the exit and top burrs in up milling and down milling are shown in Fig. 8-13.

<table>
<thead>
<tr>
<th>Test number</th>
<th>( d_x ) (mm)</th>
<th>( d_y ) (mm)</th>
<th>Spindle speed (rpm)</th>
<th>Feed rate (mm/tooth)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.0</td>
<td>2.0</td>
<td>1000</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>2.0</td>
<td>1000</td>
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</tr>
<tr>
<td>3</td>
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<td>2.0</td>
<td>1000</td>
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</tr>
<tr>
<td>10</td>
<td>4.0</td>
<td>2.0</td>
<td>1000</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 2. Workpiece material property [8]

Table 3. Different test base on cutting condition

4.3 Discussion

The predicted values and experimental values of the top burr size (thickness and height) for S45C in up milling and down milling were found to agree in most cutting conditions, Fig. 8-9. According to the top burr results for S45C, when the depth of the cut increased, the burr thickness and height also increased in up milling. The exit burr height in up milling in the cutting direction and the feed direction for S45C were mostly in the range of the experimental results in all cutting conditions while the exit burr thickness was found to agree in some cutting conditions, Fig. 10-11. It was noticed that the radial depth of the cut had an important role on the exit burr in the feed direction. The exit burr sizes increased with an increase in...
the radial depth of the cut, Fig. 11. This was because the cutting tool cut in the same position many times before leaving the workpiece edge where the rollover burr occurred. At this workpiece edge, plastic deformation increased with the ductile workpiece material (S45C), causing the exit burr to grow. It was also noticed that the top burr size increased with an increase in the axial depth of the cut, Fig. 8. With a large axial depth of cut, the cutting force is also large, which causes the top burr size to grow. The thickness and height of the top burr in down milling for FC250 and SUS304 were also found to be in the experimental range, Fig. 12-13. The system was also tested with a complex target shape. The different types of burr were recognized automatically in the different locations by different colors, Fig. 14. The green, red, blue, yellow colors represent the top burr, exit burr (rollover burr), exit burr (Poisson burr), and side burr respectively. The average thickness and height of top burr for a complex target shape are shown in Fig. 15-18. The workpiece for the target shape was S45C with the cutting condition the same as test number 1. The system can predict and display burr size and burr direction in different positions.

5. Conclusion

In this study, a burr prediction method in end milling was proposed for prediction of burr height, thickness and position in up and down milling. Two burr models, the Poisson burr and rollover burr models, were applied with orthogonal and oblique cutting. The system was developed and evaluated. It was verified that the top burr and exit burr in up and down milling for various types of workpiece materials can be predicted. The system can also predict burrs in complex target shapes, and all types of burrs can be defined with different colors and according to burr direction.

References

Fig. 11. Comparison of exit burr in feed direction (S45C).

Fig. 12. Comparison of top burr in down milling (FC250).

Fig. 13. Comparison of top burr in down milling (SUS304).

Fig. 14. Target shape (scale: top burr×25, exit burr×35).

Fig. 15. Top burr height of target shape (S45C).

Fig. 16. Top burr thickness of target shape (S45C).

Fig. 17. Exit burr height of target shape (S45C).

Fig. 18. Exit burr thickness of target shape (S45C).