Tool Paths Planning under Window Framing Scheme for Burr Minimization

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Abstract: A burr has been basically defined as a thin ridge or area of roughness produced in cutting or shaping metal. This burr leads to an undesirable workpiece edge that must be removed to enhance the level of precision of the parts. However, the cost of deburring precision components can be a significant addition to the cost of the finished parts. This paper presents a basic framework for a burr prediction system in end-milling based upon burr formation models, cutting condition, and analytical cutting force models. We developed a representation in a CAD framework to illustrate the machining process upon a PC-based NC simulator. This NC simulator can predict burr dimension and location in the end-milling process as a preventive measurement method. In addition, a tool paths planning scheme was included in the system to avoid tool exits. This method provides a feasible way for suppressing exit burr formation in an automatic manner, and thus reduce the need for deburring. The effect of in-plane exit angle was also discussed in this study. A systematic comparison of the predicted and measured burr size over a wide range of cutting conditions confirms the validity of the proposed method.

Key words: Burr prediction, Burr minimization, Cutting force model, End-milling

1. Introduction

Producing burr-free parts is prime objective of all designers in order to obtain clean and straight workpiece edges. However, edge imperfections known as burrs are often introduced to workpieces due to plastic deformation during machining. This is the main obstacle to obtaining both quality and quantity in precision manufacturing parts. In order to address this problem, a deburring or finishing operation is often required. There have been many studies on the burr formation and deburring process. They have been receiving more attention because of the increased requirement for well finished precision components and the interest in removing workers from the tedious manual work that hand deburring entails. Gillespie1 was among the first researchers to study burr formation. He classified burrs into rollover, Poisson, tear and cutoff burrs, according to the formation mechanism. He also pointed out that deburring and edge finishing of precision components may represent as much as 30% of the part cost. Although several researchers have referred to the desire to understand the formation of burr in more detail (Iwata et al23, Ko and Dornfeld24, Chen25, Hashimura13, Park26), it is still not possible to predict burr size and location accurately from basic burr formation models. However, with a combination of databases on burr properties and models of burr formation imbedded in a system to inform the designer/plant management of the effect of certain design changes on the potential for burr formation, it should be possible to reduce the occurrence and severity of burrs on precision components.

This paper presents a system for predicting the position and dimensions of burrs formed, and tool path planning for burr minimization in the end-milling process. This system is a representation in a CAD framework to illustrate the machining process upon a PC-based NC simulator that includes a database of workpiece material properties, tool geometry data, a cutting force model, cutting conditions, and a burr formation model. That information was applied to predict the burr position and dimensions. By using this approach, we can optimize the factors that affect burr formation, and thus burrs can be minimized. In the next section, theoretical modeling of burr formation is described. The mechanistic force model and burr prediction system and system verification are presented in Sections 2, 3 and 4. This study is concluded in Section 5.

2. Theoretical modeling

2.1 Theoretical modeling of burr predicting in end-milling

The most common burrs, which cause serious problems in practice, are rollover burrs and Poisson burrs. Thus, this study considers only those two burr types. A quantitative model of burr formation and fracture phenomenon in orthogonal and oblique cutting were also used in the system. Previously, the authors of this paper have validated the burr prediction model by using mechanistic Poisson burr model and rollover burr model with cutting force-modeling approach developed for end-milling1. In this study, the burr prediction model was also used; however, the cutting force model was modified and burr minimization method have been included into the burr prediction system.

2.1.1 Review Poisson burr model

The Poisson burr model suggested in Gillespie's3 work was concerned in this study. This burr occurs when the cutting tool pushes into workpiece that causes workpiece material around cutting tool edge stick out from workpiece edge, Fig. 1 (a). The Poisson burr is relatively small in size and can be defined in terms of thickness ($PB_{th}$) and height ($PB_{h}$) as shown in Eq. (1) and Eq. (2) respectively.

$$PB_{th} = R_{e} \{ \exp \left( -3 \phi_{e} \cos \phi_{e} \right) - 1 \}$$  

$$PB_{h} = \frac{d_{e} \left( 1 + \frac{1}{\sin \phi_{e}} \right) \sigma_{y} \exp \left( -3 \phi_{e} \right)}{\sqrt{3} E} \left( \frac{- \sin \phi_{e}}{2 \sqrt{3} \cos \phi_{e} + \sin \phi_{e}} \right)$$  

$$\phi_{e} = - \sin \left( \frac{\sqrt{3} P_{s}}{2 \sigma_{p}} + \frac{\pi}{6} \right)$$  

$$\phi_{e} = \sin \left( \frac{\sqrt{3} P_{s}}{2 \sigma_{p}} + \frac{\pi}{6} \right)$$  

$$P_{s} = F_{c} \times \cos \alpha - F_{r} \times \sin \alpha$$

where $R_{e}$ is the effective cutting edge radius, $\phi_{e}$ is the plasticity ellipse angle which can be found from Eq. (3), $\phi$ is shear angle in orthogonal cutting can be found from Eq. (4), $E$ is Young's modulus of workpiece, $d_{e}$ is the axial depth of the cut, $\sigma_{p}$ is the plane strain stress of the workpiece material, $\sigma_{y}$ is Poisson's ratio, $P_{s}$ is the pressure applied at the tool radius, which can be found in Eq. (5), $\alpha$, $\sigma_{y}$ and $\sigma_{p}$ are the ultimate tensile strength and yield strength of the workpiece respectively. $F_{c}$ is the main cutting force, $F_{r}$ is the cutting force in the cutting direction, and $\alpha$ is the arc length of the cutting edge in contact with the workpiece.
2.1. b Review roller burr model

Rollover burr occurs just before the cutting tool leaves the workpiece as shown in Fig. 1(b). This burr is relatively large in size and can be defined in terms of thickness \(RB_b\) and length \(RB_l\) as shown in Eq. (6) and (7) respectively.

\[
RB_b = w \times \tan \beta_b
\]
\[
RB_l = (l_c + w \times \tan \beta_b) \times \sin(\phi_l + \theta_l)
\]

where \(w\) is the initial tool distance from the end of the workpiece and is delineated by Eq. (5) and Eq. (6) for orthogonal cutting and oblique cutting respectively. \(\beta_b\) is the initial negative deformation angle and is defined by Eq. (10), \(l_c\) is the undeformed chip thickness, \(\phi_l\) and \(\theta_l\) are the rotation angles near the pivoting point on the burr side and can be defined in Eq. (11) and Eq. (12).

\[
F_r = \frac{k_f}{2} \cos^2 \beta_b - \frac{\sigma_s}{4} \tan \beta_b
\]
\[
F_w = \frac{k_f}{2} \cos \phi_l - \frac{\sigma_s}{4} \tan \phi_l
\]

\[
\frac{d}{d\beta_b} \sin \beta_b \left[ \cos \phi_l + 0.5 \cos \beta_b \right] \left[ 2 + 3 \cos \beta_b - 3 \cos(\phi_l + \beta_b) \right] = 0
\]

\[
\theta_l = \tan^{-1} \left( \frac{w}{l_c + \tan \phi_l} \right)
\]

\[
\phi_l = \tan^{-1} \left( \frac{\tan \phi_l}{\cos \phi_l} \right)
\]

where \(\lambda\) is the friction angle obtained from \(\lambda = \tan^{-1} (\mu)\), \(\mu\) is the coefficient of friction, \(\alpha\) is the rake angle in orthogonal cutting, \(\alpha_c\) is the rake angle in oblique cutting \(\gamma = \tan^{-1} \left( \frac{\sin \phi_l}{\cos \phi_l} \right)\). \(d\) is the radial depth of cut, \(k_c = \sigma_s / \beta_b\) is shear yield stress of the workpiece, \(\phi_l\) is shear angle in oblique cutting and can be defined as in Eq. (13), \(\cos \gamma = \cos \phi_l / \cos \phi_l\), \(\tan \phi_l = \sigma_s / \sin \phi_l\), \(\phi_l = \tan^{-1} \left( \tan \phi_l \cos \phi_l \right)\).

2.2 Mechanistic force model

2.2.1 Cutting forces

End-milling cutters are used extensively and usually have multiple cutting edges or flutes. In this study, a typical flat end-milling cutter with two flutes was used. A Cartesian coordinate system is defined with its origin located at the center of the end-milling. The X-axis is along the feed direction, the Y-axis is transverse to the feed direction, and the Z-axis is along the end-milling axis. Most cutting force simulation systems have used a model based on an average rigid force or static deflection model that relies on the relationship between metal removal rate (MRR), and the average power consumed in the cut. However, this method does not reflect the realistic phenomena of cutting. In this study, we have adopted the instantaneous rigid force model for prediction of cutter forces. This model provides a more realistic computation of the cutting force by computing the instantaneous force on incremental sections of the helical cutting edge for end-milling along the Z-axis. The helical end-mill can be sliced into smaller chip elements removed along the tool axis, and the cutting force is calculated on the tooth tip of each chip element removed. For a point on the \(i\)-th cutting tooth, the three cutting force components, namely the tangential \(dF_F(\theta_i)\), radial \(dF_R(\theta_i)\), and axial \(dF_A(\theta_i)\), are the cutting forces acting on a differential chip element removed, or the summing-up of cutting forces acting on an integration axial depth of cut \(d_a = d_a(n_i)\) can be given as

\[
dF_F(\theta_i) = \int_{j=1}^{n} (K_{eF} + K_{wF} + K_{aF}) \, d_{aF}(j)
\]

\[
dF_R(\theta_i) = \int_{j=1}^{n} (K_{eR} + K_{wR} + K_{aR}) \, d_{aR}(j)
\]

\[
dF_A(\theta_i) = \int_{j=1}^{n} (K_{eA} + K_{wA} + K_{aA}) \, d_{aA}(j)
\]

where \(K_{eF}, K_{wF}, K_{aF}\) and \(K_{eR}, K_{wR}, K_{aR}\) are the cutting constants in tangential, radial, and axial directions, respectively, and \(K_{eA}, K_{wA}, K_{aA}\) are the corresponding edge coefficients, \(n_i\) is number of axial integration steps and was set to 10, \(d_a\) is the axial depth of cut.

Figure 2. shows the geometry of chip thickness in up milling with the side view cutting tool sliced into small chip elements removed. The chip thickness \(t_n\) varies as a function of immersion or rotation angle \(\theta_i\) for flute \(i\) at axial depth of cut \(d_a\). The immersion angle is measured clockwise. The instantaneous effective chip thickness is expressed as

\[
t_{iF} = R - f \sin(\theta_i - d_{ai} - \tan(\phi_i)) - \frac{R^2 - f \cos(\theta_i - d_{ai} - \tan(\phi_i))^2}{R}
\]
where \( R \) is cutting tool radius, \( f = f_c / (n \times N) \) is feed rate per tooth, \( f_c \) is linear feed rate in \( \text{mm/min} \), \( n \) is spindle speed in \( \text{rpm} \), \( N \) is number of cutting edges (flutes), \( w = d_a \times \tan(\gamma) \) is flute angle, \( \gamma \) is helix angle, \( \theta \) is immersion or rotation angle for flute \( R \) can be defined as

\[
\theta = \theta_0 - (d - d_I) R \tag{16}
\]

where \( \theta_0 = \tan^{-1} + \Delta \theta \) is immersion angle of flute’s bottom edge, \( \Delta \theta \) is cutter rotation angle increment, \( \theta_0 = 2\pi/N \) is pitch angle. The elemental cutting forces can be resolved in \( X, Y, \) and \( Z \) direction as follows

\[
\begin{align*}
\frac{df_x}{d\theta} &= -\cos \theta \sin \theta - \cos \theta \sin \theta \frac{df_y}{d\theta} \\
\frac{df_y}{d\theta} &= \sin \theta \sin \theta + \cos \theta \sin \theta \\
\frac{df_z}{d\theta} &= 0 \quad 0 \quad 1
\end{align*}
\tag{17}
\]

These cutting forces are produced only when the cutting tool is in the cutting zone, that is, \( d_F \theta_0, d_F \theta_1, d_F \theta > 0 \) which mean that \( \theta_0 \leq \theta_\text{cut} \leq \theta_\text{end} \). \( \theta_\text{end} \) are cutter entry and exit angles respectively and can be defined by using width of cut \( d \) and \( R \) as below

\[
\begin{align*}
\theta_\text{entry} &= \pi - \cos^{-1}(d - d_I / R) \quad \text{up milling} \\
\theta_\text{exit} &= \pi - \cos^{-1}(d_I - d / R) \quad \text{down milling}
\end{align*}
\tag{18}
\]

In orthogonal cutting, cutting force along tool axis is zero, \( F_z(\theta) = 0 \).

### 2.2.2 Cutting constants and edge coefficients

The cutting constants and edge coefficients\(^{(13)}\) in orthogonal cutting model are express as

\[
\begin{align*}
K_C &= k_0 \sin \phi / \cos(\lambda - \alpha) \\
K_F &= k_0 \sin \phi / \cos(\lambda - \alpha) \\
K_\rho &= R_{\rho} \cos\phi \cos \delta / \sin \phi \sin \delta \\
K_\omega &= 2\sqrt{2} R_{\omega} \sin \delta
\end{align*}
\tag{21}
\]

The estimation of cutting constants in the oblique cutting model are applied from the cutting model proposed by Merchant\(^{(14)}\) and the orthogonal to oblique transformation proposed by Armarego and assuming that the Stabler rule\(^{(15)}\) is correct (chip flow angle \( \eta = \text{incinlation angle} \)).

\[
\begin{align*}
K_k &= k_0 \cos \lambda / \sin \eta \sin \phi _1 \sin \phi \sin \eta \\
K_f &= k_0 \cos \lambda / \sin \eta \sin \phi _1 \sin \phi \sin \eta \\
K_\rho &= R_{\rho} \cos \phi _1 \cos \phi \cos \eta \tan \phi / \sin \eta \\
K_\omega &= 2\sqrt{2} R_{\omega} \sin \phi _1 \sin \phi \sin \eta
\end{align*}
\tag{22}
\]

### 3. Numerical calculation of burr prediction system

The prediction system that suggested in the previous work\(^{(7)}\) is concerned with a PC-based NC simulator was used. In this study, the instantaneous rigid force model was used with the additional force at the cutting edge of the tool. The calculation of cutting constants and edge coefficients can be done by using only the basic mechanical properties of workpiece (yield strength) and fundamental principles of metal cutting. There is no experimental involve to calculate these parameters. This is big different between current cutting force model and the previous model. Previously, the authors of this paper have validated using of the mechanistic cutting forces modeling approach that used the uncut chip thickness and cutting force coefficients to predict burr size in end-milling. The previous cutting constant were derived from experimental data under various cutting conditions. However, that model is valid within the experimental ranges of speed, feed and depth of cuts only.

The numerical calculation process of burr prediction system is shown in Fig. 3. The input data is NC Program that was written in form of G-code contained in a text file. The system read information in text file for using in machining simulator. The machining simulator in this study consists of two parts, a geometry simulator and physical simulator. The geometric simulator has all necessary information about the workpiece, tool geometry, and NC data to show the machining process. By judging how the movement of the cutting tool interferes with the workpiece, the immersion angle can be 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 predicts the burr location on a display where the burrs are shown on a workpiece constructed from a Z-map model. The burr thickness and height are also calculated based on the position and type of each of the burr models applied.

![Fig. 3 Numerical calculation process](image-url)
3.2 Tool path planning for burr minimization

A good way to minimize burrs is to avoid tool exit. According to this theory, if the tool cutter exits the workpiece edge while machining, large burrs result, but this does not occur when the cutter enters the workpiece edge. The exit here refers specially to the tool cutting edge moving out of the workpiece at an edge while removing the material.

In this study, tool path planning for down-milling and up-milling were studied by using the window framing scheme method. In window framing or contour parallel milling, the cutting tool constantly engages the workpiece. It is a secure and efficient process. Another tip to add to the window framing scheme method in this study is the roll-ending technique at the corner, which provides gentle tool engagement. The roll-ending technique is also used when the tool first engages into workpiece. It is a golden rule in the milling process to make a thick chip at entrance and a thin chip at the exit, since this results in less stress on the cutting tool, ensures a stable process and saves is machine time and money. The most important point is that no tool exit produced by the window framing scheme method.

In addition to window framing, three tool path types are considered in this paper, tool path A: width of cut $d_a = \text{tool radius} R$, tool path B: width of cut $d_a < \text{tool radius} R$, tool path C: width of cut $d_a > \text{tool radius} R$, for up-milling and down-milling as shown in Fig. 4 (c). Figure 4 (a) & (b) shows the tool path planning in down milling for tool path type A (width of cut $d_a = \text{tool radius}$). The red line is the tool path planning of the tool machines workpiece. Assume that the cutting tool starts to engage from point a. After the tool approaches point b ($hc = \text{tool radius}$), the tool moves along the workpiece edge in a clockwise direction until point c. The blue line in Fig. 4 (b) is the tool path planning of the cutting tool before leaving the workpiece edge. Assume that the cutting tool starts at point M. After the cutting tool approaches point N ($NC = \text{cutting tool radius} + 1\text{mm}$), the cutting tool moves up to point Z in the Z-direction and continues to point O and then moves down to point P ($PP' = \text{cutting tool radius}$) and starts to engage the workpiece again from point P to point Q. The Z-level of points N, Q, and P are the same. The tool path method in Fig. 4 (a) and (b) can be adapted for tool path A and B but cannot be applied for tool path C. Because the tool cutting edge still moving out of the workpiece at an edge while removing the material, the method used for tool path A and B cannot be adapted for tool path C. The tool path method for tool path C has some modification as shown in Fig. 5. Assume that the cutting tool starts at point H. At point I, the cutting tool has changed direction to point J and rolls counter clockwise to point K outside the workpiece edge. The tool starts to approach the workpiece again from point K to L.

3.3 Effect of in-plane exit angle on exit burr

The in-plane exit angle $\theta_{exit}$ is defined as the angle between the cutting velocity vector $\vec{V}_c$ at the point where the tool coincides with the edge of the workpiece, and the vector that contains the theoretical edge $\vec{r}$, pointing from the tool entrance to the tool exit region.
Table 1 Evaluation for tool path generation.

<table>
<thead>
<tr>
<th>Tool Path</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up milling</td>
<td>Time</td>
<td>3min 11s</td>
<td>3min 9s</td>
</tr>
<tr>
<td>(Rollover burr)</td>
<td>Burr height</td>
<td>1mm</td>
<td>0.8mm</td>
</tr>
<tr>
<td>Down milling</td>
<td>Time</td>
<td>3min 9s</td>
<td>3min 48s</td>
</tr>
<tr>
<td>(Poisson burr)</td>
<td>Burr height</td>
<td>0.2mm</td>
<td>0.05mm</td>
</tr>
</tbody>
</table>

Table 2 Workpiece material property[8]

<table>
<thead>
<tr>
<th>Steel C: 0.45%</th>
<th>Ultimate tensile strength $\sigma_t$ (MPa)</th>
<th>Yield strength $\sigma_y$ (MPa)</th>
<th>Young’s modulus $E$ (GPa)</th>
<th>Poisson’s ratio $\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlMg0.5Si</td>
<td>569</td>
<td>343</td>
<td>205</td>
<td>0.29</td>
</tr>
<tr>
<td>AlMg0.5Si</td>
<td>152</td>
<td>90</td>
<td>68.9</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 3 Different test base on cutting condition for S45C.

<table>
<thead>
<tr>
<th>Test number</th>
<th>$d_a$ (mm)</th>
<th>$d_r$ (mm)</th>
<th>Spindle speed (rpm)</th>
<th>Feed rate (mm/tooth)</th>
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<tbody>
<tr>
<td>1</td>
<td>2.0</td>
<td>2.0</td>
<td>1000</td>
<td>0.1</td>
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<td>1200</td>
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<td>2.0</td>
<td>800</td>
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<td>9</td>
<td>2.0</td>
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<td>1000</td>
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</tr>
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</table>

5. Conclusion

In this study, a burr prediction method in end-milling was proposed for the prediction of burr height, thickness, and position in up-milling 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. The entrance burr for tool path B in down-milling seemed to be reduced, but machine time was increased, while tool path C in down-milling gave the minimum machine time but a large entrance burr. The window framing method with roll-ending technique in down-milling is a good method to avoid tool exit, thus minimizing burr and providing better cutting conditions than other window-framing methods.

References


Fig. 7: Measurement of exit burr for workpiece material steel C: 0.45% in test number 9.