Cutting Force Simulation of Machining with Nose Radius Tools

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Abstract: The mechanics of cutting with nose radius tools is discussed in the current paper. B-spline parametric curves are used to model the cutting edge and undeformed chip area. The nose area is divided into elements which are normal to the elemental cutting edge. For the rest of the chip area the approach angle remains constant; thus, there is no need to subdivide this region and is considered as a single element. The elemental area and cutting edge contact length are found with an analytical algorithm for B-spline curves intersection. Cutting force is correlated to the chip area and cutting edge with cutting coefficients which are extracted from an orthogonal database. Accordingly, the elemental cutting force components can be computed. Summing up all the forces along the cutting edge provides the resultant cutting force. In addition, experimental cutting tests have been conducted to measure the cutting components along x-, y- and z-axis. The predicted results are in good agreement with experimental observations for a wide range of cutting conditions.

Keywords: Nose-Radius tool, Cutting-Force, B-spline representation of cutting edge

1. INTRODUCTION

Cutting force in machining process if not controlled may result in reduced tool life, poor surface finish and chatter vibrations. Hence, the prediction of cutting force for different cutting conditions has been always important to manufacturing engineers. In many machining operations cutting tools with nose radius are used. The tool nose radius and the variation of oblique angle along the cutting edge result in non-uniform distribution of the chip thickness. Therefore, the chip formation is a complicated 3D process. Numerous studies have been conducted on estimating the cutting force for nose radius tools [1-6]. In order to evaluate the cutting force, all the mentioned approaches were confined at least to one of the following limitations:

1- Empirical coefficients are obtained for a certain pair of tool and work piece and a limited range of cutting conditions.
2- True process geometry is not considered and it is replaced with equivalent cutting parameters and cutting edge representation.
3- The cutting edge geometry is limited to linear and circular segments, i.e. elliptic or Spline designs are not considered.

The main purpose of the current study is to develop a methodology for predicting the cutting force of nose radius oblique tools which is not confined to the above mentioned limitations. Henceforth, the paper is organized as follows. In Section 2, the geometry of machining with a nose radius tool is discussed. The simulation methodology of machining with nose radius tools is then presented. The chip area is segmented into elements for which feed and approach angle can be considered constant. Section 3 describes the mechanics of cutting and proposes a method to compute the 3D cutting force components. The experimental setup is explained in Section 4 and in the following section, a comparison between predicted and measured cutting force components is made. Finally, Section 7 presents the conclusions of the paper.

2. GEOMETRIC MODELING

2.1. Process Geometry

The geometry of machining by a tool with nose radius (r) is shown in Fig. 1. The straight side of the tool approaches the work piece with the side cutting edge angle (λL). The tool rake face is defined by two angles, namely side rake (αs) and back rake (αb) angles. The rake face may be flat or may have chip breakers. The cutting edge consists of side, end and nose segments. However, depending on cutting conditions, one or two of the above mentioned segments may not engage the cut. The undeformed chip area depends on feed (c), radial depth of cut (DOC) and the tool geometry. It must be pointed out that the distribution of chip thickness is not uniform along the tool nose radius.
It can be shown that at any desired point along the cutting edge, the local oblique angle \( \psi \) and the normal rake angle \( \alpha_n \) can be evaluated by:

\[
i = \tan^{-1}[\tan(\alpha_n) \cos(\psi) - \tan(\alpha_D) \sin(\psi)] \quad (1)
\]

\[
\alpha_n = \tan^{-1}\left[\tan(\alpha_D) \sin(\psi) + \tan(\alpha_n) \cos(\psi) \right] \quad (2)
\]

\[
\alpha_D = \tan^{-1}\left[\tan(\alpha_D) \times \cos(i)\right] \quad (3)
\]

### 2.2. Geometric Simulation

For any cutting tool, regardless of edge geometric complexity, a series of points along the tool edge with certain increment are taken as input data points. A third degree clamped B-spline with uniform parameterization and knot span [7] is selected to interpolate input data points. The interpolated B-spline curve for the \( j \)th revolution is represented by:

\[
C_j^1(u) = N(u). P_x \\
C_j^2(u) = N(u). P_y
\]

where \( [N] \) and \( [P] \) are B-spline basis function and control point matrices, respectively. \( C(u) \) represents the whole cutting edge where \( u \in [0,1] \).

Two important parameters for nose radius tools defined as (see Fig.2 for details):

- \( u_{c1} \): The corresponding parameter of the point at which the tool curvature begins (point B).
- \( u_{c2} \): The corresponding parameter of the point at which the tool curvature ends (point D).

\[
A = \begin{bmatrix}
C_j^1(u_{c1}) \\
C_j^2(u_{c1})
\end{bmatrix} \\
C = \begin{bmatrix}
C_j^1(u_{\text{int}}) \\
C_j^2(u_{\text{int}})
\end{bmatrix} = \begin{bmatrix}
C_j^{1-1}(u_{\text{int}}^{-1}) \\
C_j^{2-1}(u_{\text{int}}^{-1})
\end{bmatrix}
\]

In order to find the \( u_{c1} \) and \( u_{\text{int}} \) a special parametric curve intersection algorithm is developed. The main steps of the proposed algorithm are as follows. The B-spline curve which represents the tool edge is first subdivided into Bezier curves over its knot span. Then, the corresponding Bezier curves of two successive B-spline curves that might intersect are extracted using the strong convex hull property of B-splines. Lastly, the intersection point is found with an analytical method called algebraic pruning which is elaborated in [8].

Once the boundary of chip load is fully defined, the total chip area \( (A_t) \) and the total cutting edge contact length \( (L_t) \) can be evaluated by:
The chip thickness and the approach angle change along the cutting edge, therefore the chip area should be segmented into elements of constant chip thickness and approach angle. The nose segment is subdivided into elements along the cutting edge, thus the chip area should be divided into elements of constant chip thickness and approach angle. Consequently each cutting force component has cutting and edge subcomponents. The cutting subcomponent is proportional to the chip area while edge subcomponent depends on cutting edge contact length. The cutting components can therefore be evaluated as follows [9, 11]:

\[
\Delta F_r = \Delta F_{ic} + \Delta F_{te} = K_{tc} \Delta A + K_{te} \Delta L,
\]

\[
\Delta F_f = \Delta F_{fc} + \Delta F_{fe} = K_{fc} \Delta A + K_{fe} \Delta L,
\]

where \( \Delta A \) and \( \Delta L \) are elemental chip area and cutting edge contact length, respectively. \( K_{tc} \) and \( K_{fc} \) are cutting coefficients and can be evaluated by:

\[
K_{tc} = \tau_s \frac{\cos(\beta_n - \alpha_n)}{\sin(\phi_n) \cos(\phi_n + \beta_n - \alpha_n)}
\]

\[
K_{fc} = \tau_s \frac{\cos(\beta_n - \alpha_n)}{\sin(\phi_n) \cos(\phi_n + \beta_n - \alpha_n)}
\]

Chip thickness ratio \( \tau_s \), shear angle \( \beta \), shear stress \( \tau_s \) and edge coefficients \( K_{tc} \) and \( K_{fc} \) are evaluated from orthogonal cutting database. \( \phi_n \) is shear angle and can be evaluated by:

\[
\phi_n = \tan^{-1} \left( \frac{\tau_s \cos(\alpha_n)}{1 - \tau_s \sin(\alpha_n)} \right)
\]

It is assumed that for each element, the Stabler’s chip flow rule applies, that is the local oblique angle \( i \) equals the chip flow angle \( \psi \). Normal rake angle \( \alpha_n \) and oblique angle \( i \) can be evaluated from Eqs. (1) ~ (3). Finally, the resultant forces for all elements can be computed by:

\[
F_x = \sum \Delta F_x \cos(\psi) + \Delta F_y \sin(\psi),
\]

\[
F_y = \sum \Delta F_x \sin(\psi) - \Delta F_y \cos(\psi),
\]

\[
F_z = \sum \Delta F_z,
\]

where \( \psi \) is the approach angle and equals to \( \theta \).

### 4. EXPERIMENTAL TESTS

Cutting tests have been conducted with carbide inserts on Al6061 T6 work piece material. Table 1 illustrates different cutting conditions of experimental tests. Cutting force components were measured with Kistler 9255b table dynamometer along with 5070 charge amplifier. A special tool holder had been designed and manufactured to mount the tool over the dynamometer, Fig. 4.
Total of 192 cutting tests were conducted to obtain appropriate orthogonal database. More than 50 cutting tests were conducted to verify the proposed model.

Fig.4. Experimental setup

Table 1. Cutting conditions of experimentations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DOC (mm)</th>
<th>c (mm/rev)</th>
<th>V (m/min)</th>
<th>r (mm)</th>
<th>$\alpha_s$ (degree)</th>
<th>$\alpha_b$ (degree)</th>
<th>$\lambda_i$ (degree)</th>
<th>$\lambda_c$ (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>0.1 - 4</td>
<td>0.02 - 0.14</td>
<td>70 - 100</td>
<td>0.4</td>
<td>-5</td>
<td>0</td>
<td>3</td>
<td>32</td>
</tr>
</tbody>
</table>

5. RESULTS AND DISCUSSION

Figures 5 to 7 compare predicted and measured cutting force components for $c=0.14$ mm/rev, $V=100$ m/min and DOC ranging from 0.1 to 4 mm.

Fig.5. Predicted and measured $F_y$ Component

Fig.6. Predicted and measured $F_x$ Component

Fig.7. Predicted and measured $F_z$ Component
Measured forces are depicted by diamonds while solid lines represent predicted values. The dashed vertical line shows DOC value equal to r. As illustrated, the predicted and measured cutting forces are in good accordance for both roughing (DOC>R) and finishing (DOC<R) operations. F_x, F_y and F_z components are predicted with an average absolute error of -1.2, 4.81 and -5.21%, respectively.

5. CONCLUSION

The mechanics of cutting with a nose radius tool is discussed in the current article. By using B-spline parametric curves to simulate the cutting process, different cutting edge geometries can be modeled. A new method is proposed to evaluate the 3D cutting force components. Experimental cutting tests have been conducted. The comparison between the predicted and measured cutting force components, verify the validity of the proposed method.

REFERENCES