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TOPOGRAPHY AND SURFACE ROUGHNESS OF FLOOR IN GROOVE MICRO MILLING

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ABSTRACT

Micro milling operation is a fabrication process to create 3D parts from tens of micrometers to a few millimeters in size using a tool with diameter less than 1mm. Micro groove is one of the common features observed in the micro parts. The surface roughness of micro grooves plays an important role in their performance. Since most of the finishing processes could not be easily performed on the micro grooves, it is of extreme importance to find a relationship between micro milling parameters and the surface roughness profile. In this paper, in order to anticipate the profile and surface roughness of the groove floor a model is proposed based on the kinematic of cutting process and tool geometry. The effects of minimum chip thickness, elastic recovery, size effect and tool deflection are included in the model. Relationship between position of points on the floor surface of groove and kinematics of cutting process are derived. In next step, simulations of proposed model are performed in the ACIS environment. Finally, using the DOE method surface roughness is investigated stochastically. The simulated and measured surface roughnesses are compared together that confirm the validity of proposed model.

Keywords: Micro milling, Surface roughness, Minimum chip thickness, Elastic recovery.

1. INTRODUCTION

Micro milling operation is one of the manufacturing methods which can produce parts with a few millimeters in size. These parts are extensively used in injection molding, Biomedical Engineering, electronic and automotive industries [1]. The most important advantage of micro milling operations rather than other micro fabrication methods is that it can produce complicated 3D parts. Since the surface topography of these parts is based on the geometrical features of tool and cutting parameters, the surface texture in this process is controllable. Finding a relationship between micro milling parameters and the surface roughness profile is very important because the surface roughness of micro parts plays an important role in their performance [2]. In micro milling, there are some phenomena which are different from traditional milling operation and can affect on the surface generation process. Due to limitations in grinding of micro tool cutting edge, micro-end-mills are always produced with a certain radius at the main cutting edge and at the tool tip edge which is one of the important characteristic of micro milling [3,4]. When the tool diameter is decreased the roundness of edge radius cannot controlled, so to prevent the tool damage the feed per tooth and depth of cut is decreased. The amount of chip thickness in micro milling usually is in the order of edge radius therefore, there is a negative Rake angle in cutting mechanism. In this common metal cutting operation, the cutting mechanisms are ploughing and shearing. The negative rake angle intensively affect on shearing and ploughing forces. This phenomenon called size effect. When the chip thickness is less than a certain value which is called minimum chip thickness, the material is elastically recovered thus no chip is formed and the cutting mechanism is mostly ploughing [2,5,6]. But, when the undeformed chip thickness exceed the minimum chip thickness, shearing takes place. Vogler et al. presented a model to predict the surface roughness using minimum chip thickness phenomenon [2]. In addition, the effect of feed rate on surface roughness of single phase material is investigated in their model. Sun et al. performed a similar study on the floor surface roughness in micro milling [7]. The floor surface roughness in micro milling is affected by several material factors: Microstructure, dynamic of the process, size effect, minimum chip thickness, etc.
thickness and elastic recovery [8]. Some factors such as the tool geometry and kinematic can also affect on the surface roughness of the floor [9].

In this paper, a mechanistic model is proposed based on the kinematic of cutting process and tool geometry in order to anticipate the profile and surface roughness of the groove floor. The effects of minimum chip thickness, size effect and tool deflection are included in the proposed model. In next step, simulation of proposed model is performed. Finally, using the DOE method surface roughness are investigated stochastically and compared with the proposed model. The results confirm a good level of accordance among proposed model, stochastic surface roughness and the measured surface roughness.

2. SURFACE ROUGHNESS OF GROOVE FLOOR

In order to anticipate the floor surface profile in groove micro milling, a model is proposed. This model is based on combination of profile of tool geometry and kinematic of the cutting process. The micro-end-mill is considered in both macro and micro scales. The tool diameter ($D$), the number of flutes ($N$) and the bottom cutting edge angle ($\alpha_e$) are macro features while the radius of cutting edge ($r_e$) and tool tip radius ($r_t$) are micro characteristics of the tool which are due to the limitation of the tool fabrication process. The path of a point on the main cutting edge is trochoidal (Fig. 1) and is given by

$$x_f = Nf_s\left(\frac{\varphi + (1-t)\frac{2\pi}{N}}{2}\right) + \frac{D\sin(\varphi)}{2}$$

(1)

$$y_f = \frac{D\cos(\varphi)}{2}$$

(2)

$$z_f = 0$$

(3)

where, $f_s$, $\varphi$ and $t$ are feed per tooth, rotation angle and the number of flute, respectively. These equations are also used for calculating the uncut chip thickness.

The tool profile at the tip includes the radius of tip tool $r_t$ and bottom cutting edge angle $\alpha_e$ (Fig. 2). The coordinates of a point on the tip of tool profile can be calculated by

$$x_p = \begin{cases} r_t \sin(\varphi)(\cos(\alpha) - 1), & \frac{3\pi}{2} - \alpha_e \leq \alpha < 2\pi \\ -r_t + \frac{r_t}{\cos\left(\frac{3\pi}{2} - \alpha_e - \alpha\right)} \cos(\alpha), & \pi \leq \alpha < \frac{3\pi}{2} - \alpha_e \end{cases}$$

(4)

$$y_p = \begin{cases} r_t \cos(\varphi)(\cos(\alpha) - 1), & \frac{3\pi}{2} - \alpha_e \leq \alpha < 2\pi \\ -r_t + \frac{r_t}{\cos\left(\frac{3\pi}{2} - \alpha_e - \alpha\right)} \cos(\alpha), & \pi \leq \alpha < \frac{3\pi}{2} - \alpha_e \end{cases}$$

(5)

$$z_p = \frac{r_t}{\cos\left(\frac{3\pi}{2} - \alpha_e - \alpha\right)} \sin(\alpha), \quad \pi \leq \alpha < \frac{3\pi}{2} - \alpha_e$$

(6)

The tool deflection due to applied cutting force will change the trochoidal motion of a point on the cutting edge. The cantilever beam theory is used to compute the tool deflection [10]. Based on this theory the tool deflection is:

$$\delta = \frac{Fl^3}{3EI}$$

(7)

where $F$, $l$, $E$ and $I$ are cutting force, beam length, elasticity modulus and moment of inertia of the cross section of the beam, respectively. Also, in the linear static analysis for determining of tool deflection the following equation can be used [11]:

$$\delta = \frac{F}{K}$$

(8)

where $K$ is the stiffness.
In order to anticipate the profile and surface roughness of the groove floor, the tool tip geometry and the kinematic of the cutting process are taken into consideration. In the global coordinate system $XYZ$ representing the primary coordinates of the system, the position of the point $p$ on the cutting edge can be specified by

$$
\begin{align*}
    x &= x_i + x_p + \delta_x \\
    y &= y_i + y_p + \delta_y \\
    z &= z_i + z_p + \delta_z
\end{align*}
$$

(9)

where $\delta_x$, $\delta_y$, and $\delta_z$ are change of cutting edge position due to tool deflection in $x$, $y$ and $z$ direction, respectively.

3. SURFACE ROUGHNESS GENERATION ALGORITHM

The profile of surface roughness of the groove is generated as follow. Series of repeated cutting edge on the path will be considered in order to model the surface roughness. Figure 3, depicts the location of repeated cutting edges on the centerline of the groove. For each step, the cutting edge profile is translated by $f_z$, repeatedly. Based on the computed tool deflection, the distance between consecutive tooth pass will be different.

Chip thickness, $t_c$, is defined as minimum distance between two consecutive profiles. At the rotation angle of $\varphi = \pi/2$, $t_c$, can be calculated by

$$
\begin{align*}
    t_c = \max\left(0, \sqrt{(x^i - x^{i-1})^2 + (z^i - z^{i-1})^2} - r_f \right)
\end{align*}
$$

(10)

where, $(x^i, z^i)$ and $(x^{i-1}, z^{i-1})$ are the center of tool tip radius at $i - 1^{st}$ increment and coordinates of the point $p$ on the cutting edge, respectively.

In micro milling operation when the chip thickness ($t_c$) is close to the minimum chip thickness, $t_{cm}$, the deformation of material is not completely plastic. The material also deformed elastically which cause a part of deformed chip recovers after removing the cutting edge. This phenomenon is referred to as elastic recovery. The value of minimum chip thickness ($t_{cm}$) is related to the cutting edge radius and the material behavior. $t_{cm}$ can be express by [4]

$$
\begin{align*}
    t_{cm} = \lambda_e r_e
\end{align*}
$$

(11)

The material removal mechanism is explained by two major cases:

Case 1: $t_c < t_{cm}$

When the undeformed chip thickness ($t_c$) is less than minimum hip thickness ($t_{cm}$) ploughing occurs. In this case, deformation is to certain extent elastic and the deformed material returns to initial place and no chip is removed.

Case 2: $t_{cm} \leq t_c$

When the undeformed chip thickness is more than the minimum chip thickness, shearing occurs and the deformed material removed as chip load.

Generated surface profile consists of the elastic recovery line in the process of ploughing region and the tool profile which located on shearing region. The elastic recovery region, the triangular shape shown in Fig. 4, is added to the region produced by the tool profile.

Figure 5 illustrated the final shape of the profile generated on the groove floor. Using the above mentioned algorithm it is possible to calculate $z(x)$ of each point on the centerline of the machined groove. Thus, the surface roughness can be anticipated.

The flowchart for the proposed algorithm is illustrated in Fig. 6. Inputs to the algorithm are tool diameter ($D$), rotation angle ($\varphi$), feed per tooth ($f_z$), cutting edge radius ($r_e$), tool tip radius ($r_f$), number of flutes ($N$), bottom cutting edge angle ($\alpha_e$) and the ratio of minimum chip thickness to cutting edge radius ($\lambda_e$). The iteration loop, starting from 0 and end to $\varphi$, is considered for the revolution increments. Counter $i$ denotes the tooth number which varies from 1 to $N$. After computing kinematics of the cutting process for the current increment (Eqs. (1), (2), (3)), the profile of the cutting is updated for the next increment (Eq. (9)). Then, the value of chip thickness is computed. If the value is greater than the minimum chip thickness, newly generated surface coordinates will be used. Otherwise, the coordinates generated in the previous increment is hold. In the next section, final shape of the remaining surface profile generated on the groove floor is saved and used for computing the surface roughness.

4. EXPERIMENTAL SETUP

The experimental investigations presented in this study were conducted in the Shien-Ming Wu Manufacturing Research Center at the University of Michigan. The Machine tool which is used in experiments is a miniaturized machine tool which is composed of tree positioning linear stages with three DC motor stages for precise positioning in the XYZ directions manufactured by SD Instruments (San Diego instrument). The overall of the machine tool is $153 \times 153 \times 153$mm$^3$ and the working space is $50 \times 50 \times 25$mm$^3$. The maximum velocity of stages is 90mm/min. An electrical NSK spindle ASTRO-E 800Z with the maximum spindle speed of 80000 rpm is used (see Fig. 7). In addition, cutting forces are measured by a Kistler 9256C1 dynamometer. The force signal is measured with a sample rate of 4KHz. The configuration of measuring system is shown in Fig. 8.

Micro-end-mills used in experimentation are PMT 2-flute tungsten carbide with tool diameter of 0.635 millimeter and the bottom cutting edge angle of 3°. Materials used in experiments are stainless steel 316. The surface roughness of floor is measured using a white light interferometer Wyko NT2000. A 1.210mm × 0.921mm area was sampled with a 10.2x optical lens (see Fig. 9).
A Philips FEI XL30 scanning electron microscope (SEM) with the maximum magnification 400000x is used to measure the tip and edge radius of micro-end-mills, which is found to be 3µm for the tip radius and 0.75µm for the edge radius, see Figs. 10 and 11. In another technique, the micro-end-mill was mounted in a polymeric resin under heat and high pressure. OLYMPUS BX60M microscope with a 1000x magnification lens was used to measure the radius of cutting edge, see Fig. 12 for details of second measurement technique. The result was closed to the value obtained from SEM pictures.

Figure 13 shows the feed marks on the floor of grooves, taken by OLYMPUS BX60M microscope with the magnification of 200x. Pictures indicate that the tooth path on the floor is trochoidal.

Figure 14 shows a sectional view of the groove centerline for the experiment with \( f_z = 12 \mu m \). This picture is taken by OLYMPUS BX60M microscope after mounted in a polymeric resin. Feed mark profiles observed at the centerline of the groove are similar to the proposed model with wavelength of 11.6µm which closed to the feed rate, \( f_z = 12 \mu m \).

In order to find the amount of minimum chip thickness some experiments are done with spindle speed 12000 rpm and depth of cut 20µm and in different feed per tooth. Figure 15 shows the pick to valley forces versus the feed per tooth in these experiments. As it is shown in this figure there is a plunge in forces plot at the feed per tooth 0.2µm. This sharp decrease in forces is due to increase in chip thickness beyond the minimum chip thickness which causes to change in material removal mechanism from ploughing to shearing. These values can suppose as the minimum chip thickness. To more confidence surface roughness of these experiments are studied. Figure 16 shows the surface roughness values Ra versus the feed per tooth in those experiments. As it is shown in this figure, Ra value has a sharp decrease at the feed per tooth 0.2µm which confirm the results of forces.

According to the result of forces and surface roughness it can be concluded that the amount of minimum chip thickness could be considered as 0.2µm. According to Eq. (11), since the value of cutting edge radius is approximately 0.75µm, the ratio of minimum chip thickness to cutting edge radius for stainless steel 316 is 0.25.

To study the machining forces and proposed model some experiments are designed utilizing the Taguchi method with three factors and three levels. In Table 1, the factors and their levels are specified for experimental cutting conditions of groove micro milling. The selected factors, which affect on the surface roughness, are cutting speed (V), feed per tooth (\( f_z \)) and depth of cut (DOC). A L_9 orthogonal array with 9 rows is implemented for the controllable factors (see Table 2).
Fig. 6   Flowchart of surface roughness computation algorithm in groove micro milling.
Fig. 7  Experimental Setup for groove micro milling.

Fig. 8  Cutting forces measuring system.

Fig. 9  The white light interferometer Wyko NT2000 for measuring surface roughness.

Fig. 10  SEM image taken from tip of micro-end-mill.
Fig. 11 SEM image taken from cutting edge of micro-end-mill.

Fig. 12 Edge radius measurement using mount resin technique.

Fig. 13 Feed marks on the floor of grooves.

Fig. 14 Sectional view of centerline of the groove.

Fig. 15 Pick to Valley Forces versus Feed per tooth.

Fig. 16 Surface roughness $Ra$ versus Feed per tooth.
Table 1  Selected factors and their levels for taguchi design of experiments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$ (m/min)</td>
<td>12</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>$f_z$ (μm/flute)</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>DOC (μm)</td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
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</table>

Table 2  Taguchi design matrix and the results.

<table>
<thead>
<tr>
<th>Ex. N.</th>
<th>$V$ (m/min)</th>
<th>DOC (μm)</th>
<th>$f_z$ (μm/flute)</th>
<th>Mean Ra (μm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>20</td>
<td>0.5</td>
<td>0.12</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>30</td>
<td>1.0</td>
<td>0.1525</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>40</td>
<td>1.5</td>
<td>0.1675</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>20</td>
<td>1.0</td>
<td>0.175</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
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<td>0.2275</td>
</tr>
<tr>
<td>6</td>
<td>18</td>
<td>40</td>
<td>0.5</td>
<td>0.2175</td>
</tr>
<tr>
<td>7</td>
<td>24</td>
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</tr>
<tr>
<td>8</td>
<td>24</td>
<td>30</td>
<td>0.5</td>
<td>0.2275</td>
</tr>
<tr>
<td>9</td>
<td>24</td>
<td>40</td>
<td>1</td>
<td>0.205</td>
</tr>
</tbody>
</table>

Figure 17 is a plot of the cutting force obtained from the experiment 3 in Table 2. As it is shown in Fig. 17 there are two peaks at each tool rotation because the tool has two flutes. Due to run out the force magnitudes are different for each flute and the forces peaks are repeated periodically. Run out causes to difference in chip load at each edge thus the force in one edge is higher than another. Also, Fig. 18 gives the FFT of the forces for this case. The tooth passing frequency 207.1Hz and the spindle frequency 103.6Hz is observed in the cutting force. In addition, Finite element analysis has been carried out to obtain the tool stiffness coefficient. The stiffness of the micro end mill was obtained by applying the load on the tool tip and calculating the deflection. The radial stiffness based on the FEM analysis was determined to be $3.8 \times 10^5$N/m.

5. SIMULATION

Solid modeling techniques provide a reliable environment for 3D part representation which makes them appropriate for micro milling geometric simulations. In solid modeling, one of the most widely used methods is Boundary Representation (B-rep). In this research, ACIS, a 3D B-rep geometric kernel, is used as a geometric engine for simulation of surface texture produced in the micro milling process [12]. The proposed mechanistic model is simulated and the surface roughness of the groove floor along the tool's centerline is computed. ACIS is a product of Spatial Corporation and it is a solid modeler based on Boundary Representation (B-rep) solid modeling techniques. B-rep can support a variety of mathematical surfaces including the most versatile one (i.e. NURBS). ACIS Scheme interface is used for developing the above mentioned simulation software. Scheme is a general-purpose functional programming language with a rich set of data types and flexible control structures [12].

Fig. 17  Plot of the measured forces in the experiment 3 in Table 2.

Fig. 18  FFT analysis of the cutting force in experiment 3.
Figure 19 shows a simulated surface texture of micro channel in ACIS environment using machining parameters such as parameters of experiment 3 in Table 2.

Having constructed the solid model of surface texture, the 2D surface profile of the channel along with the groove centerline is achieved and the value of surface roughness is computed. Simulation shows that the surface roughness in Ra scale for experiment 3 in Table 2 is 0.1779 μm. The surface profile of micro mill channel at the centerline of tool pass is depicted in Fig. 20.

In Fig. 21 the measured and predicted surface roughness are compared. The result shows that the measured and predicted surface roughnesses are in a good level of accordance thus confirms the validity of the ACIS simulation and theoretical model.

6. STOCHASTIC SURFACE ROUGHNESS

The surface roughness of the floor in micro milling is also investigated stochastically using design of experiments method (DOE). The surface roughness can be formulated with a regression model as a function of cutting conditions. Experiments are designed using the Full Factorial method. The selected factors, which affect the surface roughness, are cutting speed (V), feed per tooth ($f_z$) and depth of cut (DOC). In Table 3, the factors and their levels are specified.

In order to get reliable data each experiment is repeated. Also dry milling was applied for all experiments. The Ra values of surface roughness measurement are tabulated in Table 4. The final regression model passes all usual statistical tests of assessing including t-Tests; significance of each factors and interactions, F-Test; significance of model and the correlation factor [13]. This regression model is:

$$Ra = 0.577398 - 0.0110452 \times V - 0.0317806 \times DOC$$
$$- 0.305939 \times f_z + 0.000980774 \times V \times DOC + 0.00679912 \times V \times f_z$$
$$+ 0.000124788 \times DOC^2 + 0.0200565 \times DOC \times f_z$$
$$+ 5.84446e-007 \times V^2 - 6.10152e-006 \times V^2 \times DOC$$
$$- 0.00044049 \times V \times DOC \times f_z$$

(11)

The residual test is used to figure out the validity of the model [13]. The plot of the normal probability of the residuals in Fig. 22 shows that the points are in a straight line thus the errors are normally distributed. In addition, according to low P-value in Table 5, the importance and the validity of the regression model can be achieved. The effect of interaction factors is plotted in Fig. 23. For example, according to Fig. 23, it can be concluded that the minimum surface roughness is in the first level of the depth of cut and second level of the cutting velocity.

In Fig. 24, the mechanistic model and algorithm to predict the surface roughness Ra is compared with the regression model. The machining parameters which are used to this comparison are similar to parameters of practical tests in Table 2. As it is shown in Figs. 21 and 24, the mechanistic model is more precise than stochastic model. It is due to this fact that regression models have good interpolation but cannot response for extrapolation as well as interpolation. But as it is shown in Fig. 21 the proposed mechanistic model is proper for this range of parameters which shows that the proposed mechanistic model can anticipate the surface roughness more precise than stochastic methods.
**Fig. 22**  The plot of normal probability of residuals.

**Fig. 23**  Interaction effects of factors on surface roughness Ra.

**Fig. 24**  Comparison between surface roughnesses Ra predicted by theoretical model and regression model.
Table 3  Factors and their levels for experiments.

<table>
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<tr>
<th>Parameter</th>
<th>Level 1</th>
<th>Level 2</th>
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</tr>
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<td>$V$ (m/min)</td>
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<td>60</td>
<td>90</td>
</tr>
<tr>
<td>$f_z$ ($\mu$m/flute)</td>
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<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>$DOC$ ($\mu$m)</td>
<td>10</td>
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</table>

Table 4  Full factorial design of experiments matrix.

<table>
<thead>
<tr>
<th>Ex. N.</th>
<th>$V$ (m/min)</th>
<th>$DOC$ ($\mu$m)</th>
<th>$f_z$ ($\mu$m/flute)</th>
<th>Mean Ra ($\mu$m)</th>
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</table>

Table 5  ANOVA Table for regression model.

<table>
<thead>
<tr>
<th>Source</th>
<th>Df</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>10</td>
<td>0.0306</td>
<td>0.0031</td>
<td>22.8378</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td>16</td>
<td>0.0021</td>
<td>0.0001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>26</td>
<td>0.0328</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$S = 0.0115778$,  R-Sq = 95.40%,  R-Sq(adj) = 91.23%

7. CONCLUSIONS

In this study, a model is proposed in order to anticipate the profile and surface roughness of the groove floor in micro milling. This model is based on the combination of the profile of tool geometry and kinematic of the cutting process. The relationship between main cutting edge coordinates and kinematics of cutting process are derived. Then cutting mechanisms, the effect of minimum chip thickness and elastic recovery, size effect and tool deflection are included in the proposed model. The generated surface profile is consists of the elastic recovery line in the ploughing region and the tool profile which located on shearing region. The elastic recovery region is added to the region produced by the tool profile. Thus, the surface roughness can be anticipated. Experiments for different feed rates are performed and it can be concluded that the ratio of minimum chip thickness to the cutting edge radius for stainless steel 316 is 0.25. The proposed model is simulated in ACIS environment. Also the surface roughness is anticipated using design of experiments and regression. Results indicate that the proposed mechanistic model can anticipate the surface roughness more precise than stochastic methods.

ACKNOWLEDGEMENTS

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NOMENCLATURE

$V$ cutting speed  
$F$ cutting force  
$f_z$ feed per tooth  
$t_c$ chip thickness  
$t_{cm}$ the minimum chip thickness  
$D$ tool diameter  
$N$ number of flutes  
$T$ counter of the tooth number which varies from 1 to $N$  
$\alpha_e$ bottom cutting edge angle  
$\alpha_e$ tool edge radius  
$DOC$ depth of cut  
$\phi$ rotation angle  
$i$ counter of the iteration loop, starting from 0 and end to $\phi$  
$E$ elasticity modulus  
$I$ moment of inertia of the cross section of the beam  
$l$ beam length  
$\delta_t, \delta_r, \delta_e$ change of cutting edge position due to tool deflection in $x$, $y$ and $z$ direction  
$k$ the stiffness of the tool  
$\lambda_e$ the ratio of minimum chip thickness to cutting edge
REFERENCES


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