Modeling and Simulation Based on Morphology of Machined Surface in High-speed Milling

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Abstract: The quality of machined surface is the key and difficult point for milling hardened steel. In this work, in order to improve the quality of machined surface, study on morphology of machined surface in high-speed milling hardened steel. The model of cutting trajectory in high-speed milling hardened steel was established. By studying the measure method on micro-unit of surface texture, the simulation model of machined surfacesmorphology in high-speed milling hardened steel was established. This work researched on rule that the different parameters influenced on surface morphology with simulation. The results show that, residual surface height significantly increases with the increase of space in row spacing direction, the residual surface height increases with the increase of feed per tooth, improving spindle speed is conducive to bettering the morphology of machined surface, machining inclination angle is little effect on morphology of machined surface, the cutting vibration is conducive to bettering the morphology of machined surface when the tool amplitude was below the threshold. Copyright © 2014 IFSA Publishing, S. L.

Keywords: Hardened steel, Surface morphology, Modeling and Simulation, High-speed Milling.

1. Introduction

In view of the quality of machined surface, many scholars carried on thorough research in the world. Wang established surface roughness prediction model by regression analysis method [1]. Grzesik established surface roughness equation based on minimum chip thickness [2]. Khan and Praad researched surface roughness by using simulated annealing method [3]. Cheung studied surface roughness with multi-scale analysis methods [4]. Jiunn-Jong simulated roughness with the changes of FFT [5]. Li researched roughness by using the fractal geometry research [6]. Surech used the response surface method based on optimization of genetic algorithm to establish roughness equations [7]. A forecast method for cutting toughness was indicated by Benardos and Vassiliakos [8]. Abouelatta indicated that the major factors influence on roughness were the structures of milling cutters, feed rate and vibration in precision machining [9]. Yan established the generative model and simulation algorithm of surface morphology [10]. Chen established a new mathematical model of roughness and contour in high-speed milling [11]. Feng established the computer simulation system of surface morphology in turn-milling machining [12]. Miuzeckai researched theoretical estimates of surface profile in ball-end cutter milling [13]. A structure has been presented for roughness modeling by Chen [14]. Kochure
established a regression model fitting for process parameters in induction hardening of EN8 D steel [15]. A. K. Basu and Dayam Naveen adopted Denavit-Hartenberg technique and a number of graphical presentations in their research [16].

In high-speed milling hardened steel, the thesis aims mainly at how to create the mathematical model of cutting tool path that was under the influence of tool error and vibration, to create the simulation model of machined surface morphology, and to research the influence based on cutting parameters, the orientation of cutter, the error of tools and the cutting vibration through the morphology simulation.

2. Cutting Trajectory Model for Cutting Edge of Ball-end Milling Cutter

The surface micro-morphology are result of the ball-end cutter and the work-piece, the cutting edge of ball-end milling cutter mill the workpiece, the micro-units are formed on workpiece surface. In workpiece surface, these tiny units form the surface profiles along the tool cutting trajectory. These profiles form the morphology of machined surface. In order to get the workpiece surface morphology, need to set up the machining trajectory model of cutting contact point. Based on cutting edge of ball-end mill and the characters of workpiece surface, the contact relation of cutters and workpiece can be calculated, then the surface morphology are sure by calculating micro-units. In order to show the mutual alignment of workpiece, cutting tool and machine tooling systems, three coordinate systems are set. O_j - X_jY_jZ_j is the machine coordinate system, O_g - X_gY_gZ_g is the workpiece coordinate system, and O_d - X_dY_dZ_d is the tool coordinate system (shown in Fig. 1).

The cutters that are in high-speed milling hardened steel are mostly index-able ball-end cutter. The edge of cutter can be showed by the random-space-curve on sphere (shown in Fig. 2).

The mathematical models of machining trajectory are following:

\[
\begin{aligned}
&x_j^i = x_j^i + \Delta x_j + \frac{f \times \cos \lambda_v}{60} t + (i - 1) \times a_x \times \cos \lambda_v, \\
y_j^i = y_j^i + \Delta y_j + \frac{f \times \cos \lambda_v}{60} t + (i - 1) \times a_y \times \cos \lambda_v, \\
z_j^i = z_j^i + \Delta z_j + \frac{f \times \cos \lambda_v}{60} t + (i - 1) \times a_z \times \cos \lambda_v,
\end{aligned}
\]

where \( f \) is the cutting feed amount, \( a_x \) is the leading, \( i \) the number of tool feed, \((x_j^i, y_j^i, z_j^i)\) are the value of some point on cutting edge of tooth \( j \) in machine coordinate system when time is \( t \), \((x_j^i, y_j^i, z_j^i)\) are the value of some point on cutting edge of tooth \( j \) in tool coordinate system when time is \( t \), \((x_j^i, y_j^i, z_j^i)\) are the value of cutter coordinate system's origin in machine coordinate system, \((x_0, y_0, z_0)\) are the cutter coordinate system's origin, \((\lambda_v^x, \lambda_v^y, \lambda_v^z)\) are the vectorial angel of coordinates in machine coordinate system when it was in row spacing direction, \((\Delta x_0^e, \Delta y_0^e, \Delta z_0^e)\) are the value of tools center in tool coordinate system when there were the installation error of tool, \((\Delta x_v, \Delta y_v, \Delta z_v)\) are the value of tools in tool coordinate system when there were the deflection of cutting tool.

3. Simulation of Micro-units in Machined Surface of Hardened Steel

The metrics of surface micro-unit are the following.

1) \( h_{\text{max}} \) is the maximum residual height, it is the difference that is the highest point and lowest point of micro-units in vertically direction of workpiece surface.

2) \( h_{e1} \) is the maximum residual height of the highest point profile in row spacing direction, it is the each highest point difference that is the highest point and lowest point of micro-units in vertically direction of workpiece surface.

3) \( h_{e2} \) is the maximum residual height of the lowest point profile in row spacing direction, it is the each lowest point difference that is the highest point and lowest point of micro-units in vertically direction of workpiece surface.

4) \( h_{f1} \) is the maximum residual height of the highest point profile in feeding direction, it is the each highest point difference that is the highest point
and lowest point of micro-units in vertically direction of workpiece surface.

5) $h_f^2$ is the maximum residual height of the lowest point profile in feeding direction, it is the each lowest point difference that is the highest point and lowest point of micro-units in vertically direction of workpiece surface.

6) $l_{e1}$ and $l_{e2}$ are the distance of two highest points of micro unit in space direction.

7) $l_{e1}$ and $l_{e2}$ are the distance of two highest points of micro-unit in feeding direction micro-unit.

Measurements of micro-unit are shown in Fig.3.

The surface morphology is arranged by the micro-units, and then forms the surface texture. $\phi_\nu$ is the acute angle of texture direction and feeding direction, $\Delta\nu$ is the uniformity of surface texture. (Fig. 4).

4. Simulation of Machined Surface Morphology Based on Machining Features

4.1. The Influence of Row Spacing

The results of surface morphology simulation are shown in Fig. 5 when the cutter diameter is 20 mm, the cutting edge is flat blade, the number of teeth is 2, the machining inclination angle is 60°, the spindle speed is 3000 RPM, the feed per tooth is 0.4 mm/z, and the row spacing are respectively 0.2, 0.3, 0.4 and 0.5 mm.

Fig. 5 shows that the surface micro-unit of row spacing and feeding direction agrees with the row spacing and the feed per tooth. Fig. 6 shows that the changes of row spacing influence on residual height in row spacing direction.

![Fig. 4. Surface grain direction and measurements of uniformity.](image)

(a) 0.2 mm  (b) 0.3 mm  (c) 0.4 mm  (d) 0.5 mm

![Fig. 5. Surface morphology when the row spacing changing.](image)

Fig. 3. Measurement of micro-unit.

![Fig. 6. Trend chart of surface residual height in row spacing direction.](image)

Analysis shows that, the residual heights are made any major changes in feeding direction and the residual heights increase with the increases of row spacing in row spacing direction when the row spacing changed.
4.2. The Influence of Feed per Tooth

The results of surface morphology simulation are shown in Fig. 7 when the cutter diameter is 20 mm, the cutting edge is flat blade, the number of teeth is 2, the machining inclination angle is 60º, the spindle speed is 3000 RPM, the row spacing is 0.5 mm, and the feed per tooth are respectively 0.15, 0.2, 0.3 and 0.4 mm/z.

![Fig. 7. Surface morphology with different feed of per tooth.](image)

(a) 0.15 mm/z (b) 0.2 mm/z (c) 0.3 mm/z (d) 0.4 mm/z

4.3. The Influence of Spindle Speed

The relation of spindle speed and feed per tooth is as follow.

\[ v_f = n \cdot f_z \]  

The surface residual height decreases with the increase of spindle speed.

4.4. The Influence of Machining Inclination Angle

The results of surface morphology simulation are shown in Fig. 9 when the cutter diameter is 20 mm, the cutting edge is flat blade, the number of teeth is 2, the spindle speed is 3000 RPM, the feed per tooth is 0.3 mm/z, the row spacing is 0.5 mm, and the machining inclination angle are respectively 15º, 30º, 45º and 60º.

When change the machining inclination angle, there is not impacting the length of micro-unit, the influence on residual height is shown in Fig. 10 and Fig. 11.

Fig. 10 and Fig. 11 show that, the surface residual height decreases with the increase of machining inclination angle in row spacing direction, the surface residual heights increase with the increase of machining inclination angle in feeding direction.

![Fig. 9. Surface morphology with different machining inclination angle.](image)

(a) 15º (b) 30º (c) 45º (d) 60º

![Fig. 10. Trend chart of surface residual height in row spacing direction.](image)

![Fig. 11. Trend chart of surface residual height in feed direction.](image)
4.5. The Influence of Cutting Vibration

The deflection of cutting vibration is shown in Fig. 12.

Fig. 12. Schematic diagram of milling vibration.

The formulas on threshold of deflection amplitude are the following:

\[
A_e = \frac{r - \sqrt{r^2 - a_e^2}}{\sin \lambda}, \quad (3)
\]

\[
A_f = \frac{r - \sqrt{r^2 - f^2}}{\sin \lambda}, \quad (4)
\]

The threshold of deflection amplitude is 17.39 μm when the cutter diameter is 20 mm, the cutting edge is flat blade, the number of teeth is 2, spindle speed is 3000 RPM, the feed per tooth is 0.3 mm/z, the row spacing is 0.3 mm, and the machining inclination angle is 15º.

If the parameters that the magnitude is under the threshold are respectively 2 μm, 6 μm, 10 μm and 14 μm and the parameters that the magnitude is above the threshold are respectively 18 μm, 22 μm, 26 μm and 30 μm, the results of simulation are shown in Fig. 13 and Fig. 14.

The number of simulation is shown in Table 1.

Table 1 shows that, when the milling amplitude are below the threshold, the surface residual height remain unchanged in row spacing direction, but it increases with the increase of milling amplitude in feeding direction, the length of micro-unit remain unchanged in row spacing direction, the lengths of neighborhood sites are different (shown in Fig. 15). When the milling amplitude are above the threshold, the surface residual height remain unchanged in row spacing direction, but it is much bigger than that is below the threshold in feeding direction, the length of micro-unit remain unchanged (shown in Fig. 16).

![Fig. 13. Simulation results of milling amplitude below the threshold.](image1)

(a) 2 μm  (b) 6 μm

![Fig. 14. Simulation results of milling amplitude above the threshold.](image2)

(a) 18 μm  (b) 22 μm

(c) 26 μm  (d) 26 μm

<table>
<thead>
<tr>
<th>The deflection of cutting vibration (μm)</th>
<th>$R^e_\lambda$ (μm)</th>
<th>$R^f_\lambda$ (μm)</th>
<th>$\ell_\mu$ (μm)</th>
<th>$\ell$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.087</td>
<td>0.870</td>
<td>0.3</td>
<td>0.3004, 0.2996</td>
</tr>
<tr>
<td>6</td>
<td>1.086</td>
<td>0.875</td>
<td>0.3</td>
<td>0.3013, 0.2987</td>
</tr>
<tr>
<td>10</td>
<td>1.087</td>
<td>0.882</td>
<td>0.3</td>
<td>0.3022, 0.2978</td>
</tr>
<tr>
<td>14</td>
<td>1.085</td>
<td>0.886</td>
<td>0.3</td>
<td>0.3031, 0.2969</td>
</tr>
<tr>
<td>18</td>
<td>1.032</td>
<td>4.498</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>22</td>
<td>1.032</td>
<td>3.571</td>
<td>0.2998</td>
<td>0.6</td>
</tr>
<tr>
<td>26</td>
<td>1.032</td>
<td>3.569</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>30</td>
<td>1.032</td>
<td>3.567</td>
<td>0.3</td>
<td>0.6</td>
</tr>
</tbody>
</table>
When the milling amplitude are below the threshold, the direction of texture is consistent with the direction of feed because the surface residual heights in row spacing direction are much bigger than that in feeding direction, the surface texture are evenly distributed. When the milling amplitude are above the threshold, the length of micro-unit remains unchanged, but it is bigger and twice as well off as that the milling amplitude is below the threshold. Adjusting the fix-errors of cutter, the effect of vibration in cutting and cutting may be effectively eliminated.

5. Conclusions

In this work, the cutting trajectory model of cutting edge of ball-end milling cutter is established, the simulation model of machined surfaces morphology that mills the free-form surface of hardened steel in high-speed is established, obtain measurement method of machined surface micro-unit, and then obtain influence rule on surface-morphology based on machining features by simulation. The result shows that,

1) The residual heights increase with the increases of row spacing in row spacing direction.

2) The surface residual heights significantly increase with the increase of machining inclination angle in feeding direction.

3) Improving the spindle speed is helpful to improve the quality of surface-morphology.

4) The ranges of residual heights are not too extreme when change machining inclination angle.

5) The residual heights increase with the increase of milling amplitude in feeding direction when the milling amplitude is below the threshold; it is much bigger than that is below the threshold in feeding direction when the milling amplitude is above the threshold.

References

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