INFLUENCE OF TOOL ORIENTATION ON THE MACHINING MECHANISM OF BALL-NOSED END MILLING

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1. Introduction

Ball-nosed end milling has been applied widely in the machining of sculptured surfaces, for example the metal dies and molds for the plastic injection molding or the press working. In order to machine the products in high accuracy, there have been reported many studies on ball-nosed end milling. The most distinguishing characteristic of ball-nosed end milling is that the tool rotation axis is inclined against the normal direction of the workpiece as shown in Fig. 1. The influence of the tool orientation to the machining mechanism is studied before. The influence to the machining resistance is researched by Mounayri(1) in the experimental way. Ikua is investigate the geometric relationship between the tool orientation and the undeformed chip thickness (2)(3). But the direction of the tool orientation is limited only toward up and down or along contour line. As the experiment is difficult for efficiency or repeatability, the study about the effect on the machining accuracy of the tool orientation is very few.

This paper presents originally the experimental measurement method of the machining accuracy in the ball-nosed end milling. This method provides very efficient and accurate experiment, and the machining test with any tool orientation can be done. Several experiment was worked out, some measuring result of the machining error and the surface roughness is presented.

2. Influence of the tool orientation

2.1 Definition of the tool orientation

In this study, we must discuss about the influence of the tool orientation against the surface of the workpiece. So the definition of the tool orientation is the most essential factor for this discussion. Fig.2 illustrates the definition of the tool orientation. Z axis is the normal direction of the surface of the workpiece in machining. Y axis is the direction of feeding the tool. So x axis is the direction of the pickfeed. On this coordination 2 angles are defined for the tool orientation. One is the angle between z axis and a plane including the tool rotation axis and y axis. It is called “the angle of pick feed direction \( \omega_p \)”. In this case we define another coordination \( x,y,z_t \). This coordination is inclined \( \omega_t \) around y axis. So \( y,z_t \) plane include the tool rotation axis. In this plane the angle between the tool rotation axis and \( z_t \) axis is called “the feed direction angle \( \omega_f \)”. And other cutting conditions to use explanation of the following are shown in Table 1.
2.2 Geometric influence for generating the machined surface

The main cause of the machining error on ball-nosed end milling is considered the elastic deformation of tool in short time machining. The elastic deformation depends on the machining resistance. And the machining resistance is affected by the cutting area obtained by the calculation of the undeformed chip thickness. In this reason the geometric analysis of the undeformed chip thickness for ball-nosed end milling is very important for considering about the machining accuracy. The cutting area at generating the surface or variation of cutting area probably affect to the machining accuracy. When the tool orientation change some direction, the machining accuracy is different from each other. Many people knows about this thing, but no one knows the reason or the best direction of the tool orientation. Fig.3 shows the cutting area change with the tool orientation as same cutting condition. Fig.3(a) is the case that the cutting area becomes large, and Fig.3(b) is the case of the small one. The shape of removal volume is almost same, but the sweeping direction of the cutting edge into the workpiece is different. So the machining error is different as the tool orientation is changed.

2.3 Geometric analysis of the cutting area

The authors have already developed the geometric analysis method of the cutting area for the ball-nosed end milling \(^{(4)-(7)}\). The sample of the variation of the cutting area changed the tool orientation is shown in Fig.4.

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**Table 1 Notations**

<table>
<thead>
<tr>
<th>Tool geometry</th>
<th>Cutting conditions</th>
<th>Tool orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball radius (mm)</td>
<td>Feed per revolution (mm/rev.)</td>
<td>Inclination angle to pickfeed direction (rad.)</td>
</tr>
<tr>
<td>Number of teeth</td>
<td>Depth of cut (mm)</td>
<td>Inclination angle to feed direction (rad.)</td>
</tr>
<tr>
<td>(R)</td>
<td>(f)</td>
<td>(\omega_p)</td>
</tr>
<tr>
<td>(n)</td>
<td>(a)</td>
<td>(\omega_f)</td>
</tr>
</tbody>
</table>

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**Fig. 3** Effect of the tool orientation on the cutting area

(a) Cutting area is large

(b) Cutting area is small

**Fig. 4** Example of the cutting area analysis in various tool orientations
The relationship between $\alpha$, $\beta$, $\omega_p$, and $\omega_f$ is expressed as eq.(1).

$$
\omega_p = \sin^{-1}(\sin \alpha \cos \beta)
$$

$$
\omega_f = \tan^{-1}(\tan \alpha \sin \beta)
$$

$$
\alpha = \cos^{-1}(\cos \omega_p \cos \omega_f)
$$

$$
\beta = \tan^{-1}\frac{\sin \omega_p}{\tan \omega_f}
$$

In this report the feed direction angle $\beta$ is detailed in Fig. 6. The tool is started at the outside point of work-piece and is fed inside. The appearance of the experiment is shown in Fig. 7. The workpiece is fixed to the table directly. 8 types of the tool orientation can be done in same time using 55mm diameter round bar. In addition the pre-finishing is machined with same settings. So any difference exists with one inclination angle. This is another profit of this method.

3. Cutting experiment

This report is presented the new method of experiment for measuring the machining accuracy with any tool orientations. This method makes it possible to machine in every tool orientation with the three-axis-controlled machine tool. The first characteristic point is that the round bar with inclined surface is used. On this surface the tool is feed with some angle. The inclination angle of surface is $\alpha$, and the feed direction along this surface is $\beta$ as shown in Fig. 5.

$$
\omega_p = \sin^{-1}(\sin \alpha \cos \beta)
$$

$$
\omega_f = \tan^{-1}(\tan \alpha \sin \beta)
$$

$$
\alpha = \cos^{-1}(\cos \omega_p \cos \omega_f)
$$

$$
\beta = \tan^{-1}\frac{\sin \omega_p}{\tan \omega_f}
$$

The profile curve is measured using by the noncontact 3-dimensional measuring instrument. This instrument is applied with the semiconductor laser, the resolution is 10nm and measuring range is 10mm depth. An example of measurement is shown in Fig. 8. Before the measured path cutting 2 paths are carved slightly on both side for making reference line. The bottom of 5 paths are measured each, and the actual depth of cut is obtained by averaging. The difference between the preset depth of cut and real one is the machining error. The positive value means the over cutting and the negative value means the less cutting.
3. Result of experiment

3.1 Machining error

Some experimental results are shown using new method above. The material of workpiece is 0.45% carbon steel. The ball-nosed end mill is the throw-away type with 2 straight blades. The tool material is the cemented carbide. The cutting conditions are as follows; \( R=5 \text{mm} \), \( n=2 \), \( t=0.1 \text{mm/rev.} \), \( p=1 \text{mm/track} \), \( a=0.5 \text{mm} \) just same as Fig. 4. The spindle speed is 5000rpm. The inclination angle \( \alpha = \pi/12, \pi/6, \pi/4 \text{ rad.} \) and the feed direction angle \( \beta = 0, \pi/4, \pi/2, 3\pi/4, \pi, 5\pi/4, 3\pi/2, 7\pi/4 \). The results are shown in Fig. 9. At \( \beta = 0 \text{rad.} \) the machining error becomes steady in every inclination angle. And at \( \beta = \pi/2 \) the measurement value is not steady, so the machining error is very different as \( \alpha \) is changed.

The tendency to overcut is found in \( \alpha = \pi/12 \text{rad.} \) and the tendency of contrary is found in \( \alpha = \pi/4 \text{ rad.} \). This is intriguing result, so it must be investigated by more carefully.

3.2 Surface roughness

The surface roughness can be measured using the noncontact 3-dimensional measuring instrument. At \( \beta = 0 \text{rad.} \), the cutter mark is found very clearly. At \( \beta = \pi/4 \text{ rad.} \) to \( \pi/2 \) the shape of cutter mark is collapsed gradually. So the surface roughness becomes larger. In other inclination angle the surface roughness becomes small at \( \beta = 0 \text{rad.} \) and \( \pi \text{rad.} \). On the other hand the surface roughness becomes large at \( \beta = \pi/2 \text{rad.} \) and \( 3\pi/2 \text{rad.} \). It depends on the direction of the cutting edge sweeping.

4. Conclusions

1) The experimental measurement method of the machining accuracy in the ball-nosed end milling is presented. This method provides very efficient and accurate experiment.

2) The influence of the tool orientation to the machining accuracy is clarified in experimental. So the tendency to overcut and another tendency with the inclination angle is observed.

3) The surface roughness is varied as the feed direction is changed. This phenomena depends on the direction of the cutting edge sweeping.

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