Study on Cutting Mechanism and Cutting Performance of Inclined Surface Machining with Radius End Mill *

—Comparison with Cutting Method of Contouring Path and Scanning Path —

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Abstract: This paper deals with an analysis of the cross-sectional chip area and cutting performance of radius end milling of an inclined surface using a contouring and scanning cutter path method. At first, the modeling of a cutter, an edge, a rake surface and a workpiece with an inclined surface are carried out using 3D-CAD. Secondly, the cross-sectional chip area is calculated by the interference of the rake surface and the uncut chip volume. The influence of the cutting method and the direction of pick feed on the behavior of the cross-sectional chip area. And also, the influence of the inclination angle of the machined surface on the maximum cross-sectional chip area is shown. In addition, the cutting force and surface roughness are measured by cutting tests and the cutting processes are examined. Finally, cutting conditions which would produce a good cutting performance are considered.

Key words: radius end mill, cutting mechanism, cutting performance, 3D-CAD, cross-sectional chip area, inclined surface machining, cutting force, surface roughness, contouring path, scanning path

1. Introduction

Recently, radius end mills have been developed in order to machine highly accurate and efficient three dimensional shapes. The machining process of a radius end mill is very complex, because the cutting edge shape of a radius end mill is very complex, as with a ball end mill. A few papers regarding radius end mills are reported and classified into four groups: (1) cutter path for a three dimensional shape using 3 or 5 axis control machining(1-4), (2) analysis of machining error using cutter-swept envelopes(5), (3) prediction of machining error(6) and (4) comparison of cutting properties by a ball end mill and a radius end mill. According to these past papers, the cutting mechanism and performance of a radius end mill were unclear and the guiding principle was not obtained for the actual tool being used.

Therefore in this paper, the modeling for a tool, an edge, a rake surface and a workpiece are defined and an analysis of the cutting machining the inclined surface using a contouring and scanning cutter mechanism for practical use is done using 3D-CAD with a similar method as reported previously(7). Firstly, the analysis is performed for machining the inclined surface using a contouring and scanning cutter path method, and an accurate cross-sectional chip area which varies according to the cutter rotation and feed are calculated. Next, the cutting force and surface roughness are measured by experiments under various cutting conditions. Then, the cutting process and performance of the radius end mill are considered. In addition, cutting conditions which would produce ideal cutting performance will be discussed.

2. Modeling and calculating method of cross-sectional chip area

Figure 1 shows the connected model of a tool, an edge and a workpiece for the calculation of the cross-sectional chip area, and the axis of coordinates and symbols used. Fig. 1 (a) shows the cutting model for a contouring cutter path method and Fig.1 (b) shows that for a scanning cutter path method. Cutting is performed by the movement of the tool in the feed direction with the condition of radial depth of cut $R_d=0.6$ mm. $P_T$ is a pick feed and Fig.1 (a) shows the case of stepped down pick feed given to the lower direction and Fig.1 (b) shows the case of downward pick feed as the minus X direction along the inclined surface respectively. The area denoted as “abcd” shown in Fig.1 is the uncut chip volume removed by one cutting operation.

Figure 2 shows the projected uncut chip volume “abcd” on the X-Y plane and the relationship to the volume and cutting edge positions passing the uncut chip volume, and the calculation method of the cross-sectional chip area. From Fig. 2, the cutting operation basically begins from the position at Edge 1, through the position of Edge 2 and finishes at the position of Edge 3. The cross-sectional chip area $A$ is the intersected part with the uncut chip volume and the rake surface.
including the cutting edge of the tool. The area denoted as “kmm” shown in Fig.2 is the cross-sectional chip area with Edge 2. Calculation of the cross-sectional chip area \( A \) is performed by conditions shown in Table 1. The standard angle of a cutter rotation \( \theta = 0^\circ \) is the position where the center part of the cutting edge coincides with the Y axis.

3. Experimental method

The machine tool, the tool, the workpiece and the measuring apparatus used are as follows:

<table>
<thead>
<tr>
<th>Machine tool</th>
<th>NC vertical milling machine (Osaka-kiyo, MHI-350)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool</td>
<td>radius ( R_c = 6.0 \text{mm} ), corner radius ( CR = 3.0 \text{mm} ), helix angle ( \eta = 30^\circ ), 1 tooth (one of two teeth is removed), (TiAl)N coating, carbide solid tool</td>
</tr>
<tr>
<td>Workpiece</td>
<td>carbon steel (S45C), 70x50x10mm</td>
</tr>
<tr>
<td>Apparatus</td>
<td>dynamometer (Kistler, 9257A), roughness tester (Tokyoosumitsu, SURFCOM 130A)</td>
</tr>
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</table>

Cutting tests were carried out under the conditions shown in Table 1. Cutting formations were up and down milling with a stepped up and stepped down pick feed with a contouring cutter path and upward and downwards pick feed with a scanning cutter path. Roughness tester. In all cutting tests, jigs with an inclined surface of \( \alpha = 0 \) to 75° and the plate-type workpieces were used.

4. Calculations, experimental results and discussions

4.1 Cross-sectional chip area

Figure 3 shows the influence of the cutting formation on the cross-sectional chip area using the horizontal axis with the cutter rotational angle. Calculation results of a contouring and scanning cutter path method with the workpiece inclination angle \( \alpha = 15^\circ \) and the corner radius \( CR = 3 \text{mm} \) are shown in Fig. 3(a) and 3(b) respectively.

From Fig.3(a), variation of the cross-sectional chip area with up and down milling shows symmetry with respect to the \( \theta = 0^\circ \), because the shape of the uncut chip volumes removed by both milling processes are symmetrical with respect to the Z-Y plane. Additionally, the range of the cutter rotational angle when cutting with stepped down pick feed is longer than that with stepped up pick feed. Contrarily, the maximum cross-sectional chip area of the former is smaller than that of the latter.

Therefore, the straight cutting edge on the middle part of the tool is used on the former case and the circular cutting edge on the outside is used on the latter case. From Fig. 3(b), variation of
the cross-sectional chip area is basically the same as in Fig.3(a). However, the difference of variation of the cross-sectional chip area between upward and downward pick feed and the up and down milling is not so large respectively. Thus, the shape of the uncut chip volume removed by the scanning cutter path method is almost symmetrical with respect to the Z-Y or Z-X plane.

Figure 4 shows the maximum cross-sectional chip area \( A_{\text{max}} \) using the horizontal axis with the workpiece inclination angle \( \alpha \), and comparison of two types of cutter path methods: the contouring and scanning method in Fig.4(a) and 4(b) respectively. From Fig.4(a), \( A_{\text{max}} \) by stepped down pick feed is smaller than that by stepped up pick feed. While in the case of Fig.4(b), the variation of \( A_{\text{max}} \) is almost the same in upward and downward pick feed, however the \( A_{\text{max}} \) slightly increases when angle \( \alpha \) increases in a range of more than 15°. Assuming the cutting force is almost in proportion to the cross-sectional chip area, it is expected that good performance machining is achievable by selecting a scanning cutter path method and contouring cutter path method with stepped down pick feed.

4.2 Cutting force

Figure 5 shows the three cutting force components and resultant force \( F \) when cutting is performed using a contouring cutter path method, a stepped up pick feed in Fig.5(a) and a
scanning cutter path method, upward pick feed in Fig.5(b). In addition, both figures show results obtained during down milling with a workpiece inclination angle \( \alpha = 15^\circ \) and corner radius \( CR = 3\,\text{mm} \). The tool used has one cutting edge and the actual cutting range \( q \) from beginning to ending are 27.0 and 62.2° are shown respectively. From Fig.5(a), \( F_x \) component is biggest when the maximum value \( F_{x_{\text{max}}} \) is 80.5N and 1.3 times that of the \( F_y \) component. In the case of the scanning cutter path and upward pick feed shown in Fig.5(b), \( F_y \) component is biggest when the maximum value \( F_{y_{\text{max}}} \) is 28.7N. However, the maximum value \( F_{y_{\text{max}}} \) obtained by the scanning method is smaller than that of \( F_{x_{\text{max}}} \) obtained by the contouring method. Additionally, the components \( F_z \) obtained by both methods show very small value because of the outer edges contribute to the machining with both cutter path methods.

Figure 6 shows the maximum resultant cutting force \( F_{\text{max}} \) in various cutting conditions and the results by pick feed and workpiece inclination angle. In the case of contouring cutter path method shown in Fig. 6(a), the \( F_{\text{max}} \) of stepped up pick feed is bigger than that of stepped down pick feed. In addition, the \( F_{\text{max}} \) increases as the workpiece inclination angle increases. This is the reason why the cross-sectional chip area of stepped up is larger than that of stepped down and the area increases as increase of the workpiece inclination angle \( \alpha \) increases. However, there is not a precise correlation between the difference of the \( F_{\text{max}} \) shown in Fig.4(a) and that of the \( F_{\text{max}} \) shown in Fig.6(a) under the stepped up condition. In addition, the reason for the above results is unclear. So, this problem is an issue that needs to be taken up in the future.

In case of scanning cutter path method shown in Fig.6(b), the difference of the \( F_{\text{max}} \) between upward and downward is small. This is the reason why the cutting force is mainly affected by the cross-sectional chip area. These results are almost identical to the results shown in Fig.4(a) and (b) respectively.

### 4.3 Surface roughness

Figure 7 shows roughness curves of a machined surface with a workpiece inclination angle of \( \alpha = 15^\circ \) in Fig. 7(a) and 7(b) and \( \alpha = 45^\circ \) in Fig. 7(c) and 7(d). Additionally, Fig.7 shows the results indicated in Fig.7(a) and 7(c) which were performed with a contouring cutter path and a stepping up pick feed. Fig.7(b) and 7(d) indicate results with a scanning cutter path and an upward pick feed. From Fig.7, the tool mark is discernable due to the pick feed, and the roughness \( R_z = 14.3 \) and 15.0μm measured by Fig.7(a) and 7(c) in the condition of a contouring cutter path method are almost the same as the theoretical value \( R_{th} = \frac{P_t}{2R_s} \), \( R_{th} = CR = 15\,\text{μm} \). In the case of a scanning cutter path method, the

![Fig.7 Roughness curve](image_url)
roughness \( R \approx 3.3 \) and 6.6 \( \mu m \) measured by Fig.7(b) and 7(d) are smaller than these with the contouring method. This is the reason why the radius of the curvature of the cutting edge projected in the feed direction increases as the workpiece inclination angle \( \alpha \) decreases.

Figure 8 shows the theoretical roughness \( R_{th} \) shown in Fig.1 of the machined surface using a radius end mill for two types of cutter path methods. These values are obtained as the distance from the peak to the valley of the surface using 3D-CAD. However, in the condition of contouring when the range of \( \alpha = 5.7^\circ \) \( = \sin^{-1}(P \gamma 2CR) \) to \( 84.3^\circ \) \( = \cos^{-1}(P \gamma 2CR) \) these values are able to calculate by the equation described above. In Fig. 8, with the exception of angles ranging near 90°, the value for for the scanning method is smaller than that for the contouring method. Therefore highly accurate machining is achievable by selecting the scanning cutter path method in finishing.

Figure 9 shows the roughness \( R_z \) of the machined surface under various cutting conditions. In addition, Fig. 9 shows comparisons of the influences of the workpiece inclination angle, pick feed direction and cutter path method on the roughness. In Fig.9, the experimental value is almost equal to the theoretical value indicated by the dotted lines. These findings clearly verify that the calculation method of the theoretical roughness using 3D-CAD is suitable.

5. Conclusions

In this research, the cutting mechanism and cutting performance of inclined surface machining with a radius end mill are investigated. The main results obtained are as follows.

(1) 3D-CAD models for a radius end mill and an inclined workpiece are shown and the cross-sectional chip area is calculated accurately by the intersection of the rake surface with the uncut chip volume.

(2) The maximum cross-sectional chip area \( A_{max} \) obtained by stepped down pick feed is smaller than that by stepped up pick feed when using a contouring cutter path method. Additionally, \( A_{max} \) by downward pick feed is smaller than that by upward pick feed when using a scanning cutter path method.

(3) The maximum cutting force \( F_{max} \) obtained by a scanning cutter path method is smaller than that by a contouring cutter path method.

(4) Theoretical roughness of a contouring and scanning cutter path method is calculated using 3D-CAD and it is verified that the calculating method of theoretical roughness is accurate because experimental values are almost identical to theoretical values for both cutting path methods.

(5) It is shown that highly accurate machining is achievable when selecting a scanning cutter path method in finishing based on experimental and calculated results.

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