Analysis of Cutting Mechanism by Ball End Mill Using 3D–CAD*
(Chip Area by Inclined Surface Machining and Cutting Performance Based on Evaluation Value)

Hiroyasu IWABE**, Keisuke SHIMIZU*** and Mitunori SASAKI****

This paper deals with an analysis of the chip area by ball end milling of an inclined surface using a contour 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 chip area is calculated by the interference of the rake surface and the chip volume. The influence of the cutting method and the direction of pick feed on the behavior of the chip area and the influence of the inclination angle of the machined surface on the maximum chip area are shown. And, the evaluation value $E_d$ for cutting performance with the multiple by the chip area and the distance from the spindle axis to the center of gravity of the chip area is proposed. The evaluation value of the condition by stepping up pick feed and the inclination angle $\alpha = 20^\circ$ shows minimum, so a good cutting performance would be expected for these cutting conditions.

Key Words: Ball End Milling, Cutting Mechanism, 3D–CAD, Chip Area, Inclined Surface, Cutting Performance, Evaluation Value

1. Introduction

Ball end mills are useful cutters for machining a three dimensional shape, such as molds or dies. Then, many tools with various shape and dimensions are developed and available. Recently, according to developments in tool coating technology(1), direct milling for hardened steel has become possible using such tools(2). And the importance of ball end mills is increasing.

But, the machining process by a ball end mill is very complex, because of an intermittent cutting and a changing of chip thickness during cutting. In spite of the difficult cutting mechanism with a ball end mill, many papers reported and they are grouped as follows. (1) cutting force measurement and prediction(3)–(9), (2) generation of machined surface(10)–(16), (3) cutting performance by a special tools(17)–(19), (4) regenerative cutter vibration(20),(21), (5) tool life and machining accuracy(22)–(25), (6) fabrication of tools and cutting characteristics(26),(27) and (7) surface roughness and optimum cutting condition(28),(29). The above studies indicate much useful knowledge, but it is not clear as to chip area accurately during cutting.

Therefore in this paper, the modeling for a tool, an edge, a rake surface and a workpiece are made out and analysis of the cutting mechanism for practical use is tried using 3D–CAD. The analysis is performed for machining the inclined surface using a contour line tool path method, and the accurate chip area which varies due to the cutter rotation and feed are calculated. And also, the evaluation value for the cutting performance with the multiple by the chip area and the distance from the spindle axis to the center of gravity of the chip area is proposed and the influence of inclination angle and cutting methods on the cutting performance are compared.

2. Modeling and Calculating Method of Chip Area

2.1 Modeling

Figure 1 shows the modeling method of a tool, a cutting edge and a rake surface using 3D–CAD (CATIA-V5), and the procedures are as follows.

(1) Define the rectangular 3 axes ($X$, $Y$ and $Z$) and the original point as $O(0,0,0)$. 

* Received 8th September, 2005 (No. 05-4157) 
** Niigata University, 8050 Ikarashi 2-nocho, Niigata 950–2181, Japan, E-mail: iwabe@eng.niigata-u.ac.jp 
*** Incs Inc., Nishi-shinnjyuku, Tokyo 163–1452, Japan 
**** CS. Technica Co., 677–15 Ichibamachi, Outa 373–0013, Japan
(a) (b) (c)

Fig. 1 Method of 3D–CAD modeling of cutting edge and ball end mill

(2) Make Z axis the central axis and define the cylinder of the radius \( R_c = 10 \) mm in the position of \( Z = -10 \sim 20 \) mm.

(3) Define the helical edge \( QQ' \) (broken line) of 30° helix angle on the surface of the cylinder under the condition with passing the point \( P_0 \) (10,0,0).

(4) Define the hemisphere of the radius \( R_c = 10 \) mm in the cylinder with the center point \( O \) (0,0,0) in the position of \( Z = -10 \sim 0 \) mm.

(5) Move the part of edge \( P_0 Q' \) on the hemisphere surface toward the Z axis, and define the edge \( Q_0 P_0 O_2 \).

(6) Define the rake surface generated by scanning the line \( O_1 Q \) along the Z axis \( O_1 O_2 \) and the edge \( Q_0 P_0 O_2 \).

Figure 2 shows the modeling method of a workpiece in the same manner, the procedures are as follows.

(7) Define the line \( ST \) as \( 4R_c \) length on the \( Y \) axis.

(8) Define the right-angled triangle \( STU \) of which the base is the line \( ST \) and the angle of inclination is \( \alpha \).

(9) Move the right-angled triangle \( STU \) with \( 4R_c \) distance in the \( X \) direction and define the right-angled triangle \( S'T'U' \).

(10) Define the workpiece with the volume indicated by \( STU'T'S' \).

Fig. 2 Method of 3D–CAD modelling of workpiece

Cutting is performed by the movement of the tool in the \( X \) direction in the condition of radial depth of cut \( R_d = 1.0 \) mm. \( P_f \) is a pick feed and Fig. 3 shows the case of a stepped down pick feed given in the lower direction along the inclined surface. Original point \( O \) is the center of the hemispherical part of the tool, the broken line indicates the cutting edge. The part \( abcd \) shown in Fig. 3 is the chip volume removed by one cutting operation. The chip volume is enclosed by the part surface of cylinder bcd, the two part surfaces of hemisphere abd and abc and the part surface of the inclined surface acd.

Any cutting edge point \( P_c \) \((X_c, Y_c, Z_c)\) on the ball part of the tool is calculated by the Eq. (1), assuming that the intersecting point of the longitude line passing the point \( P_c \) and the \( X-Y \) plane is \( P_0' \) and angle \( \phi \) of \( P_0 O' \) is \( \phi \).

\[
\begin{align*}
X_c &= R_c \sqrt{1 - (Z_c/R_c)^2} \cos \phi \\
Y_c &= -R_c \sqrt{1 - (R_c/Z_c)^2} \sin \phi \\
Z_c &= -R_c \phi / \tan \eta
\end{align*}
\]

The cutting edge shape projected on the \( X-Y \) plane of end part of a ball end mill available on the market is measured by the digital microscope (Keyence VH-6300). Figure 4 shows the result by the measurement and the estimated shape calculated by the Eq. (1). From Fig. 4, the both cutting edge shape are almost coincident and the error of cutter rotation angle \( \delta_c \) at each edge point is less than \( \pm 3.7^\circ \). Then, it is verified that the definition method of the cutting edge is almost proper.

2.2 Calculating method of chip area

Figure 5 shows the projected chip volume abcd on the \( X-Y \) plane and the relationship to the chip volume and cutting edge positions passing the chip, and the calculation method of the chip area. By Fig. 5, the cutting operation basically begins from the position at edge 1, through positions of the edge 2 and 3 and finishes at the position of the edge 4.

The chip area \( A \) is the intersected part by the chip vol-
3. Calculated Results and Considerations

3.1 Influence on pick feed direction and cutting method

Figure 6 shows the difference of the chip area using the horizontal axis with the cutter rotational angle and parameter as inclination angle by down milling. Calculation results by stepping up and stepping down pick feed are shown in Fig. 6 (a) and (b) respectively.

In the condition of $\alpha = 0^\circ$, the chip area becomes greater slowly with the increase of the cutter rotational angle and after reaching the maximum value decreases quickly in case of a stepped up pick feed. But, in case of a stepped down pick feed, the difference of chip area reverses in regard to the rotational angle and both shapes are symmetric with respect to the $\theta = -90^\circ$.

On the other hand, increasing the inclination angle, the chip volume moves far away from the original point O and the range of cutter rotational angle during actual cutting decreases. And each maximum chip area becomes almost constant in the conditions of the inclination angle $\alpha$ is more than $15^\circ$. Because, the chip volume removed by one cutting operation is independent on the inclination angle and the angle $\beta_p$ indicates almost constant value. However, the shape of the chip volume reverses up and down for two type pick feed direction and each angle $\beta_p$ exists from $29.2^\circ$ to $38.2^\circ$ in case of a stepped up pick feed and from $53.9^\circ$ to $57.5^\circ$ in case of a stepped down pick feed. It is the reason why the maximum chip area becomes different with pick feed direction. Where, the difference of the chip area from the inclination angle $\alpha = 0^\circ$ to $15^\circ$ arises in the moving process of the top edge of the tool from being on the surface abc of the chip volume to out side of the abc, and the angle $\beta_p$ increases with the above process.

And in case of a stepped up pick feed and $\alpha = 75^\circ$, the cutting operation occurs by the cutting edge of the ball and cylinder part of the tool simultaneously, the maximum chip area decreases. Then, we define a special ball end mill again the shank radius of which is smaller than the edge radius shown in Fig. 7. Using this ball end mill, inaccurate intersection of the tool and workpiece at $\alpha = 75^\circ$
does not occur, and a correct calculation of the chip area can be achieved. The result is shown by the broken line in Fig. 6 (a).

Figure 8 shows the chip area calculated by the condition of up milling with the same axes of coordinates as Fig. 6. In case of up milling, the shape of chip area indicates basically reverse in regard to the rotational angle compared with the results shown in Fig. 6. Because, the chip volume removed indicates a reversed shape, both chip volume for up and down milling becomes symmetric in respect to the Y axis. And the range of cutter rotational angle during actual cutting decreases in the same way as Fig. 6 with an increase of the inclination angle $\alpha$. But the maximum chip area decreases in case of a stepped up pick feed shown in Fig. 8 (a), and decreases once time till $\alpha = 30^\circ$ then increases in case of a stepped down pick feed shown in Fig. 8 (b). It is the reason why the edge of the ball end mill used is straight shape in the center part of the tool and circular shape on the outside. While, in the case of a stepped up pick feed and $\alpha = 75^\circ$, the calculation of the chip area is performed with the special ball end mill shown in Fig. 7 and the result is shown in Fig. 8 (a) by a broken line in the same way as Fig. 6 (a).

Figure 9 shows the relationship between the inclination angle and the maximum chip area using the results shown in Figs. 6 and 8. From Fig. 9, in case of a stepped up pick feed and down milling, the values show almost
the same value and indicate maximum for any inclination angle. In case of up milling, the maximum chip area decreases with an increase of the inclination angle, and indicates the minimum value for the angle which is more than $\alpha = 45^\circ$.

The other side, in case of a stepped down pick feed and $\alpha = 20^\circ$ the maximum chip area indicates minimum. After that, the value tends to increase slightly with an increase of the inclination angle and indicates almost the same as the value by a stepped up pick feed and up milling condition for the angle which is more than $\alpha = 45^\circ$. And the minimum value at $\alpha = 20^\circ$ is almost one half of the maximum value by a stepped up pick feed and up milling condition.

### 3.2 Evaluation value and cutting performance

A cutting operation with a ball end mill is performed by the spindle rotation and the table feed of a machine. If the working point of the maximum cutting force on the tool which is in proportion to the maximum chip area described above becomes near to the spindle axis, the cutting torque will be controlled and lead to improvement of the cutting performance. Then, at first assuming the cutting force will act by concentrated force on the point G of the chip area, and next define the evaluation value $E_d$ by the Eq. (2). Here, $A$ is the chip area and the length $L_G$ is the distance from the spindle to the point G. The value $E_d$ corresponds with the cutting torque which is one of cutting performance. Assuming the tangential component of the cutting force increases with increase of the chip area, it is possible to compare the cutting performance by the value $E_d$.

$$E_d = A \cdot L_G$$

Figure 10 shows the evaluation value $E_d$ calculated by Eq. (2) with cutting conditions same as Fig. 6. Figure 10(a) shows the result by a stepped up pick feed and Fig. 10(b) shows that of a stepped down pick feed respectively. From Fig. 10, the variation of the evaluation value $E_d$ is basically same as Fig. 6, but the value $E_d$ increases with an increase of the inclination angle, because of the length $L_G$ increases with increase of the inclination angle.

Figure 11 shows the maximum evaluation value $E_{d_{\text{max}}}$ with the inclination angle. From Fig. 11, the value $E_{d_{\text{max}}}$ indicates minimum in case of a stepped down pick feed and $\alpha = 20^\circ$. It means for inclined surface milling

![Fig. 9 Maximum chip area and inclination angle of workpiece](image)

![Fig. 10 Relationship between evaluation value and rotational angle of cutting edge (in case of down milling)](image)

![Fig. 11 Maximum evaluation value and inclination angle of workpiece](image)
that the optimum cutting performance corresponding to the cutting torque will be realized by the condition of a stepped down pick feed and using the machine tool which spindle axis inclines 70° to the surface of the workpiece that will be machined. And also, it is expected that the operation due to the above cutting condition leads to the highest machining efficiency especially in roughing.

However, in this paper, it is assumed that the surface abc and abd of the chip volume shown in Fig. 3 are spherical surfaces. Then the analysis described above is available on the limited conditions of a relatively small feed $S_z$ compared with the tool radius $R_c$.

4. Conclusions

(1) 3D–CAD models for a ball end mill, a rake surface with a cutting edge and an inclined workpiece are shown.

(2) The defined edge shape is almost coincident to that of the tool available, so the appropriateness of the modeling method is verified.

(3) Defining the removed chip volume, the chip area is calculated accurately by the intersection of the rake surface with the chip volume during a cutter rotation.

(4) The difference of chip area shows reversed behavior in respect to the rotational angle for up and down milling and for a stepped up and stepped down pick feed respectively.

(5) The maximum chip area indicates the largest value by a stepped up pick feed and down milling and almost 2 times larger as the value of a stepped down and up and down milling.

(6) The easy evaluation value for cutting performance is proposed and it is shown that the optimum cutting performance will be realized by the conditions of a stepped down pick feed and $\alpha = 20°$, because of the evaluation value indicates minimum value with the above condition.

Acknowledgement

The authors wish to express their thanks to Tsubanex Co. for modeling by 3D–CAD and Mr. H. Takahashi and Mr. H. Miwa, Graduate School of Science and Technology Niigata University, for calculation.

References


JSME International Journal


