Study on Cutting Mechanism and Cutting Performance of Machining for Curved Surface by Ball End Mill using 3D—CAD

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Abstract:
This paper deals with the cutting mechanism and cutting performance by ball end milling of curved surface. Firstly, the modeling of a cutter and a workpiece with a concave curved surface are carried out using 3D-CAD. Secondly, the chip area is calculated by the interference of the rake surface and the chip volume removed by a single cutting operation. The maximum chip area shows transitional phenomenon, then a new cutting method such as a looped cutter path machining is proposed and the effectiveness of the new method is considered and verified using the evaluation value which is calculated by the multiplication of the chip and the length from Z axis to the gravity of the chip area.

Keywords: Ball end mill, Cutting mechanism, 3D-CAD, Chip area, Curved surface, Cutting performance, Looped cutter path machining method.

1. Introduction
Ball end mills are useful cutters for machining a three dimensional shape, such as molds or dies. Then, many tools with various shapes and dimensions have been developed and made 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 have been produced and they are grouped as follows. (1) cutting force measurement and prediction [3-6], (2) generation of machined surface [7-10], (3) cutting performance by a special tools [11-13], (4) regenerative cutter vibration [14], (5) tool life and machining accuracy [15-17], (6) fabrication of tools and cutting characteristics [18,19], (7) surface roughness and optimum cutting condition [20,21] and (8) chip area and evaluation value [22]. The above studies provide much useful knowledge, but chip area during cutting is not accurately clear.

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 curved surface using a contour line tool path method, and the accurate chip area which varies due to the cutter rotation and feed are calculated. However, the maximum chip area shows transitional phenomenon, and it is difficult to maintain constant cutting conditions. Then, a new cutting method named looped cutter path milling is proposed. The effectiveness of the new method is considered and verified using the evaluation value which is calculated by multiplication of the chip and the distance from the spindle axis to the center of gravity of the chip area.

2. Modeling and calculating method of chip area
2.1 Modeling
Figure 1 shows the modeling method of a tool and a cutting edge 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 Oc(0,0,0).
(2) Make Z axis the central axis and define the cylinder of the radius Rc=10 mm in the position of Z=-8 ~ -16 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 Po(8,0,0).
(4) Define the hemisphere of the radius Rc=10 mm in the cylinder with the center point Oc(0,0,0) in the position of Z=-8 ~ 0 mm.
(5) Move the edge PoQ’ on the hemisphere surface toward the Z axis.

Figure 2 shows the model of workpiece using same 3D-CAD, and the procedures are as follows.
(6) Define the rectangular 3 axes (X,Y and Z) and the original point as Oc(0,0,0).
(7) Make Z axis the central axis and define the cylinder of the radius Rc=10 mm in the position of Z=-8 ~ 16 mm.
(8) Define the helical edge QQ’ (broken line) of 30° helix angle on the surface of the cylinder under the condition with passing the point Po(8,0,0).
(9) Define the hemisphere of the radius Rc=10 mm in the cylinder with the center point Oc(0,0,0) in the position of Z=-8 ~ 0 mm.
(10) Move the edge PoQ’ on the hemisphere surface toward the Z axis.

Figure 2 shows the model of workpiece using same 3D-CAD, and the procedures are as follows.
(6) Define the trapezoid STUV on Z-X plane.
(7) Move the trapezoid STUV in the minus Y direction and define the volume STUV-stuv.
(8) Rotate the trapezoid STUV 90° in the clockwise and define the volume S’T’U’V’.
(9) Move the trapezoid S’T’U’V’ in the minus X direction and define the volume S’T’U’V’-s’t’u’v’.
(10) Define the workpiece model by combination above three volumes.
Figure 3 shows the connected model of the tool and the workpiece for the calculation of the chip area and the gravity of the chip area, and the axis of coordinates and symbols used. A cutting is performed by the moving of the tool along the inclined and curved surface on the i-j plane which is parallel to the X-Y plane in the condition of radial depth of cut Rd=0.8 mm. The definition of the i-j coordinate is shown in Fig.3 as the original point Oc and each direction is tangential and normal to the circle of the looped path respectively described later. \( \alpha \) is an inclination angle and Pf is a pick feed. Fig.3 shows the case of stepping down pick feed given to the lower direction along the inclined surface.

The cutting edge shape projected on the X-Y plane of the 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 equation (22). 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 i-j plane and the relationship to the 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 edges 2 and 3 and finishes at the position of edge 4.

The chip area A is the intersected part by the chip volume and the rake surface including the cutting edge of the tool, and the inclined line part klmn is the chip area by edge 3. Calculation chip area are performed under conditions shown in Table 1 and the standard angle of a cutter rotation \( \theta =0^\circ \) is the position that the center part of the cutting edge coincides to the j axis.
3. Calculated results and considerations

3.1 Influence on pick feed direction and cutting method

Figure 6 shows the variation of the chip area using the horizontal axis with the cutter rotational angle and parameter as the radius of the cutter path $\rho$. And also, the calculation result of milling at the inclined surface is added on Fig.6 by the cutting conditions of down milling, $\alpha=60^\circ$ and stepping up pick feed. From Fig.6, the chip area increases rapidly just after the start of curved surface milling, and after reaching maximum value decreases slowly. And the actual milling stops at the spindle rotation angle $\theta=30^\circ$. Decreasing the radius of cutter path $\rho$, the maximum chip area increases greatly. The value of maximum chip area reaches about 2 times larger than that of inclined surface milling, and the range of spindle rotation angle regarded with milling becomes about 1.8 times greater.

Figure 7 shows the variation of chip area using the same coordinates as Fig.6 and parameter as the inclination angle $\alpha$ and the radius of cutter path $\rho$. The radius $\rho$ are greatly different, however the range of the $z$ coordinate of the cutter center Oc is small as $Zc=5.5$–$8.8$ mm. Then calculated results shown in Fig.6 are that by milling at near the bottom part of the
workpiece. From Fig.7, the chip area by the condition of stepping up pick feed indicates larger a value than that of stepping down, and the maximum value of the former becomes almost twice that of the latter.

In ball end milling, the removed chip volume is not changed by the difference of inclination angle. But the chip volume moves from the portion of the cutter center and milled by the near straight edge at cutter center part to the radial direction of the cutter center and milled by the curved edge at the outside part, then the chip area becomes increased. And also, for the same reason as described above, the maximum value increases with the increase of inclination angle.

Figure 8 shows the difference of maximum chip area using the horizontal axis with the radius curvature of cutter path and parameter as inclination angle. Fig.8(a) is the result of up milling and Fig.8(b) is that by down milling. Both figures are shown by the condition of stepping up pick feed and each result by inclined surface milling is plotted on the position with regard to the radius cutter path at the top surface described by dotted line.

In the case of Fig.8(a) at first, the maximum chip area increases with decrease of the radius of curvature due to the increase of inclination angle, the chip area shows the transitional phenomenon. In the condition of workpiece height H=25 mm, the range of the radius of curvature of the workpiece is limited with the inclination angle. But the larger the inclination angle, the bigger the increasing rate of the maximum chip area becomes.

The value increases rapidly with the value \( \rho \) achieves to zero indicated the vertical axis of Fig.8. And the difference between the value by curved surface at the each right end value indicated by dotted lines and that by inclined surface becomes larger with increase of inclination angle.

By the way, in the case of down milling described in Fig.8(b), the maximum value becomes slightly larger compared with that of up milling. But the influence of the radius of cutter path and the inclination angle of the workpiece on the maximum chip area are almost the same as up milling. And in case of the stepping down condition, results of which are not shown in this paper, the influence of the radius of curvature \( \rho \) and inclination angle \( \alpha \) of the workpiece on the maximum chip area give almost the same as results shown in Fig.8 respectively.

3.2 Improvement by looped cutter path

In curved surface milling, the chip area increases with small radius of curvature of the workpiece shown in Fig.8. And it is predicted the cutting force becomes large in proportion to the chip area. By the results, the deflection of the cutting tool and workpiece become large and it is difficult to perform a uniform machining accuracy obtained by milling for the inclined surface. Then we propose and try the looped cutter path indicated by the dotted circle shown in Figure 9. Namely in Fig.9, when the cutter center reaches point \( P_1 \) from \( P_s \), the
cutter moves around a circle counterclockwise from point P1 to P1 the radius of which is \( \rho_1 \) \( (\rho + dx) \) and its center is \( O_1 \). After roughing by these cutter paths, the finishing of the curved surface is performed.

Further, in this study, the loop radius \( \rho_1 \) is obtained by the numerical calculation as the maximum chip area of finishing and that of roughing are almost equal. The value \( \rho_1 \) for each condition is calculated by the same idea described above, because of the value changes with the height and radius of curvature of the workpiece which will be machined.

Figure 10 shows the improvement effect of the maximum chip area by the looped cutter path, at \( \phi=45^\circ \), because the effect is most clear at this angle. From Fig.10, the maximum chip area (mark : \( \triangle \)) decreases one half by conventional machining (mark : \( \square \)). The maximum chip area by finishing (mark : \( \times \)) almost coincides with the result of inclined surface milling (mark : \( \circ \)) and that by a looped path for roughing. From Fig.10, it is clear that the transitional phenomenon is controlled. And also, behavior of the chip area of roughing by looped cutter path is almost the same as those of finishing and inclined surface milling, then tripartite machining is balanced.

3.3 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 in 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 maximum evaluation value \( E_{max} \) by the Equation (1). Here, \( A_{max} \) is the maximum chip area and the length \( L_G \) is the distance from the spindle to the point \( G \) of the chip area \( A_{max} \) and the cutting performance is compared by the value \( E_{max} \).

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E_{max} = A_{max} \cdot L_G
\]  

Figure 11 shows the maximum evaluation value \( E_{max} \) with the inclination angle. From Fig.11, the value \( E_{max} \) indicates minimum in the case of a stepping down pick feed and \( \alpha=20^\circ \). It means for a concave curved surface milling that the optimum cutting performance will be realized by the condition of a stepped down pick feed and using the machine tool with a spindle axis which inclines 70° to the surface of the workpiece that will be machined.
4. Conclusions
(1) 3D-CAD models for a ball end mill, a rake surface with a cutting edge and an inclined workpiece with curved and inclined surface are shown.
(2) 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.
(3) The maximum chip area indicates the largest value for concave curved surface milling by stepping up pick feed reached to almost 1.8 times larger as the value of that of inclined surface.
(4) A new cutting method, such as the looped cutter path method is proposed and it is verified that the chip area is controlled by the new method.
(5) Using the easy evaluation value, it is shown that the conditions of $\alpha = 20^\circ$ and stepped down pick feed is recommended for a concave curved surface machining from a view of the cutting performance.

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References