Influence of Cutter Orientations on Cutting Force in Ball End Milling of TC17

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Abstract. In order to improve the ball end milling multi-axis milling titanium alloy workpiece machining method, the influence of cutter orientations on cutting force is studied in this paper by experiment. This paper uses the tool rotation angle and the tool inclination angle to describe the cutter orientations. Analyse the cutting force under different milling posture. The results prove that, when the tool inclination angle is constant, the change of tool rotation angle will cause changes in the value and direction of the cutting force. Though maintain the tool rotation angle, the change of the tool inclination angle will change the cutting speed, thus make the cutting force decrease first then increase.

Introduction

With the development of manufacturing industry, more and more sculptured surfaces have been used in practical production involving aerospace, automobile, and general machinery. Ball end mill is widely used in the multi-axis finishing. It has complex geometry, due to the high machine tool spindle speed in machining process, the cutting force is greatly affected by cutter orientations. When the tool axis is perpendicular to the machining surface, the cutting speed of the cutter center is zero, and effective capacity chip space is very small, easily cause the blade broken, thus affect the processing quality and increase the processing cost.

At present, there are many researches on the influence of cutter orientations on cutting force. The researches of C.K. Toh show that when high-speed milling quenched steel, using negative top lead angle, the cutting force is larger than using positive top lead angle [1]. Gani studied the effect of tool inclination angle on surface quality in 5-axis ball-end milling [2]. Aspinwall has found that resultant cutting force was highest with the 0° workpiece tilt angle operation as a consequence of the ploughing action occurring at the center of the milling tool axis (zero cutting speed) [3]. In order to obtain the relation between the inclination angle and machinability, a machining inclination angle of 15° is the best, and a down milling method is recommended for generating tool paths in the CAM system [4]. Lan has found that adjusting the inclination angle between ball end milling cutter axis and workpiece machining surface can effectively improve the cutting conditions, decrease the cutting force, reduce vibration caused by process system and improve the quality of workpiece surface [5]. Fu has found that, with the increase of the angle $\beta$ between tool axis and the feed direction, the cutting force is reduced; but when the tool inclination angle $\beta$ reaches 15°, during the increase of the inclination angle, the decrease of the cutting force is no longer apparent [6]. Chen has found that when using the high
speed steel ball end mill to machine duralumin, the large value of the inclination angle is not better, because larger angle will cause larger axial cutting force, thus lower the surface quality [7].

This paper uses the tool rotation angle and the tool inclination angle to describe the cutter orientations, studied its influence on cutting force by single factor experiment. Optimized tool inclination angles were suggested according to the experimental results and detailed analysis. A better understanding of multi-axis milling process with tilt and lead angles was made.

The Cutting Force Experiment of Cutter Orientations

The Analysis of Ball-end Cutter Cutting Speed under Different Inclination Angle

Because of the angle between the tool axis and machining surface, the effective tool cutting diameter changes, the actual cutting speed changes, as shown in Fig1. .

![Figure 1. The sketch map of cutter contact area.](image)

![Figure 2. Four typical cutter orientation.](image)

The size of $\eta$ can be calculated by the Eq. 2-1:

$$\eta = ar \cos \left[ \left( R - a_p \right) / R \right] .$$

(2-1)

It is easy to know that the highest cutting speed point is close to the side of the blade, through geometrical relationship we can get the following conclusions:

When material on the left side of the position OF shown in Fig. 1, if $\theta - \eta > 0^\circ$ ,cutter center of the ball-end cutter don't participate in cutting, and the minimum cutting speed is $v_i = v_{\text{max}} \times \sin (\theta - \eta)$ (E). When material on the right side of the position OF, if $\theta + \eta < 90^\circ$, the side edge of the ball-end cutter don't participate in cutting, the highest cutting speed is $v_h = v_{\text{max}} \times \sin (\theta + \eta)$ (G); the cutting speed of maximize cutting depth (F) is $v = v_{\text{max}} \times \sin \theta$ .

The Analysis of Ball-end Cutter Contact Area under Different Rotation Angle

The tool rotation angle can affect the cutter contact position. As shown in Fig. 2, a, b, c, d respectively is the cutting tools orientations in the tool inclination angle of 30°, the tool rotation angle of 0°, 90°, 180° and 270°.
Different tool rotation angle has different cutter contact area. Fig. 3 shows the cutter contact area in four cutter orientations. In the situation a and b, the cutter contact area is located in F-G area which the linear velocity is relatively high, in the situation c and d, the cutter contact area is E-F where the linear velocity is relatively low.

**Experiment Scheme and Testing Technology**

The main purpose of this experiment is to research the influence of different cutter orientations on cutting force. In the first experiment, the tool inclination angle is 30°, then change the tool rotation angle. In the second experiment, the tool rotation angle is 30°, 60°, change the tool inclination angle.

The experimental material is TC17, tool is 7 diameter 4 teeth cemented carbide ball-end cutter. Cutting tool lead angle is 3°, first clearance angle is 10°, the second clearance angle is 20°, spiral angle is 40°. The machine tool is MIKRON UCP 1350. Cutting parameters is finish contour parameters: main shaft speed n=5000r/min, feed engagement $f_z=0.06\text{mm/mm}$, depth of cut $a_p=0.3\text{mm}$, width of cut $a_e=0.35\text{mm}$. The experiment uses three-way piezoelectric dynamometer Kistler 9255B to measure the cutting force.

**Research on Cutting Force**

**The Influence of Tool Rotation Angle on Cutting Force**

The force is measured on the workpiece. In Fig. 6, $F_x$, $F_y$, $F_z$ is the cutting force peak value which does not include direction. When tool inclination angle is 30°, change tool rotation angle, cutting force has obvious ups and downs. When tool rotation angle is 0°, 180°, 300°, cutting force obtain the minimum value. From the beginning of 0°, resultant tool force increases with the increasing of tool rotation angle. When the tool rotation angle is 120°,
resultant tool force obtains the maximal, then falling until tool rotation angle 180°, the force reaches the trough. As the tool rotation angle continues to increase, cutting force fluctuate within a certain range.

Figure 6. The relationship between the cutting force and the tool rotation angle.

The cutting force of ball-end cutter not only has its peak change, in every cycle (4 blade cutting time, in the test, a cycle is 12ms), its waveform also has big difference.

Figure 7. Gesture a (tool rotation angle 0°). Figure 8. Gesture b (tool rotation angle 90°).

From the cutting force waveform figure of the gesture a, we can find that, the cutting force on Fx is the largest, it’s also the main cutting force and changes intensely. When in the gesture b, the peak cutting force on Fy direction is the same as feed direction, cutting force of Fz direction is main cutting force, the peak value of force of two direction appear at the same time.

Figure 9. Gesture c (tool rotation angle 180°). Figure 10. Gesture d (tool rotation angle 270°).
When the cutting tool is in the gesture $c$, cutting force of each tooth is equilibrium. When the cutting tool is in gesture $d$, the cutting force on the $F_y$ direction changes intensely, the cutting force on the $F_x$ direction increase and become the main cutting force. The cutting force reach the peak every two teeth. Originally, for cutting force waveform, four blade is a cycle, now two blade is a cycle. Because the contact area is very close to the point. Let the cutting condition: tool radius $R = 3.5 \text{ mm}$ and cutting depth $a_p = 0.3 \text{ mm}$ plug in Eq. 2-1, we get $\eta = 24^\circ$. The distance between cutting contact point and cutter heart \[ r = R \sin(\theta - \eta) \approx 0.4 \text{ mm}. \] In the actual processing, ball-end cutter is composed of two long blade and short blade, under the test conditions, two short blade in this gesture can't completely remove all materials, long blade can remove at once, eventually form the waveform shown in the Fig.10.

The causes of this phenomenon is mainly the change of unit time cutting area. Through Fig. 3, we can find that compared with $b$ and $d$, the unit time cutting area of gesture $a$ and $c$ is small, and the time of force effect is short, thus cause the lower cutting force. From a to b, the cutting area is getting larger, so that the cutting force increase until the largest cutting area of gesture b-c (tool rotation angle 120°). For the same reason, the cutting force decrease until gesture c because of the change of the unit time cutting area.

The Influence of Tool Inclination Angle on Cutting Force

A second test results is shown in Fig. 11, when tool rotation angle is 30°($X_1, Y_1, Z_1$) and 60°($X_2, Y_2, Z_2$), the relationship between cutting force and the tool inclination angle.

![Figure 11](image)

Figure 11. The relationship between the cutting force and the tool inclination angle.

It can be seen in the Fig.11 that when the tool rotation angle is 60°, the cutting force is bigger. Whatever the tool rotation angle is 30° or 60°, the cutting force appears down before rising. When the tool inclination angle is close to $0^\circ \sim 20^\circ$, the force is larger. When the tool inclination angle is between $30^\circ \sim 60^\circ$, the force has no obvious change, though the tool inclination angle is 70°, the cutting force rises abruptly.

![Figure 12](image)

Figure 12. Tool rotation angle 30°.
In every cycle (4 blade cutting time, a cycle is 12ms), the waveform of cutting force has big difference. As shown in Fig. 12 and Fig. 13, when tool inclination angle is 30°/36°, the value of the cutting force on $F_x,F_y,F_z$ is nearly the same, change rule is similar, cutting force is small. When tool inclination angle is 75°/72°, the cutting force changes intensely, and its value is larger.

The causes of this phenomenon is mainly the increase of cutting speed. From the section 2-2, we know $\eta=24°$, when the tool inclination angle $\theta=0°$, the highest possible speed of the contact area $v_h=44.7m/min$, cutting speed is low and the cutting force is big. When $\theta=30°$, $v_h=90m/min$ reach 80% of the highest speed($v_{max}=110m/min$), because derived function of the $v_h$ formula is cosine function, thus cause the larger cutting force. The growth of the $v_h$ become slow after 30°, changes of the cutting force in this interval is not very big. But when $\theta=70°$, $\theta + \eta = 94° > 90°$, it can be seen in Fig. 2 that side of the blade was also involved in cutting, this make radial cutting force increases, reduce the cutting tool rigidity thus intensify vibration, led to the increase of cutting force.

**Summary**

First this paper use NX 8.0 to geometrical analysis the cutting conditions of ball-end cutter in different gesture, second experimental study on the cutting force of ball-end cutter in different gesture. Results show that, under the same cutting condition, different gesture has a great influence on the machining process and the results. We can get the following conclusions:

(1)Maintain the tool inclination angle, the change of the tool rotation angle will change the cutting area, thus change the value and the direction of the cutting force. When the rotation angle is 0°, 30°-60°, 180° and 300°, the cutting force is more stable and smaller.

(2)Maintain the tool rotation angle, the change of the tool inclination angle will influence the cutting speed, thus cause the cutting force decrease first then increase. When the tool inclination angle is 30° ~60°, we can get smaller and more stable cutting force.

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