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ORIGINAL ARTICLE

Effects of tool orientation and surface curvature on surface integrity in ball end milling of TC17

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Abstract Tool orientation has an important effect on the surface quality of a free-form surface during ball end milling process, and the selection of tool orientation is important to ensure the surface quality. In this work, a series of milling experiments were performed by using a carbide ball end mill on a workpiece of TC17 titanium alloy. The purpose of this study was to determine the tool orientation producing optimal surface integrity. The results showed that the surface roughness in both directions was better when the rotational angle was within the range of 0°~90° and with a constant inclination angle. In addition, inclination angle had little effect on the roughness in the feed direction, whereas a much larger or smaller angle led to greater roughness in the step direction. The tool orientation strongly affected the surface morphology. Compressive residual stress was detected on all machined surfaces. The maximum surface residual stress was obtained when the rotational angle was 90°, and the surface residual stress decreased as the inclination angle increased. On this basis, four curved surface models with different curvatures were established according to the features of a blade, and the effects of inclination angle and cutter path orientation on surface integrity were studied. The results indicated that the surface roughness produced with an upward orientation varied more than that produced with a downward orientation for a steep curved surface; the value of the roughness was small for a horizontal orientation and when the machine surface was very smooth. The machined surface for a flat curved surface was smoother, and there were no obvious differences in surface morphology between the two cutter path orientations. For steep curved surfaces, the cutter path orientation had no obvious influence on the residual stress, and a greater value was obtained when the surface was much steeper. For flat curved surfaces, the residual stress had no obvious variation resulting from small changes of the inclination angle.

Keywords Titanium alloy · Ball end mill · Tool orientation · Surface curvature · Surface integrity

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1 Introduction

The milling process, an important method of forming the complex surfaces of components, is widely used in the CNC machining. Ball end mill is extensively used in the multi-axis finish machining of curved surfaces, owing to its better adaptability, and the tool orientation has a significant effect on surface quality. In addition, satisfactory surface integrity has important effects on the fatigue performance, corrosion resistance, stability and reliability of components. The work in [1] provided the experimental results of the effect of four kinds of integration processes on surface integrity and fatigue property, the results have shown that the milling surface texture has a uniform circular arc peaks and valleys distribution and that the longest fatigue life can be obtained by using the milling, polishing, shot peening and polishing integration processes.

Various studies on the effects of tool orientation on the surface integrity during ball end milling have been conducted. Toh [2] has focused on the high-speed milling of hardened steel and reported that a large cutting force was obtained when a negative lead angle was used, the minimum surface roughness was obtained when a positive lead angle was used. Gani et al. [3] have discussed the effect of tool orientation on the cutting process in five-axis milling by using the geometric model of the machining process, and have experimentally verified their conclusions. Chen et al. [4, 5] have investigated the multi-axis milling theory and revealed the effects of various tool orientations on the surface integrity of steel. Daymin et al. [6] have reported that the best surface finish was obtained when the inclination angle of workpiece was 25°, and the mean surface stress decreased slightly as the inclination angle increased. Ko et al. [7] have focused on the inclination angle and cutter path by considering the cutting force, surface roughness and tool wear. The results indicated that a 15° inclination angle was optimal and that down milling with a downward cutting orientation was the best cutter path. Aspinwall et al. [8] have studied the effects of tool orientation and workpiece inclination angle on surface integrity. They have reported that the horizontal downward cutting orientation provides a better surface quality, and the largest residual stress was obtained when there was no workpiece inclination angle. Kalvoda et al. [9] have indicated that a positive or negative lead angle and tilt angle have little effect on the residual stress, they obtained the best surface roughness when both angles were negative and obtained the worst surface roughness when there was no inclination. Lim [10] has focused on the high-speed finish machining of a blade using a ball end mill and investigated the effects of four different cutter path orientations on the elastic deformation of the blade, surface roughness and surface morphology. The results indicated that the horizontal downward cutting orientation satisfied the processing requirements in multi-axis CNC machining. Zhao et al. [11] have established a surface morphology prediction model during ball end milling process and simulated the influence of the workpiece inclination angle on the surface morphology, residual height and two-dimensional contour. Their results have indicated that the optimal angle is 15°.

A complex curved surface is usually composed of many curved surfaces with different curvatures. Because it is widely used in various fields, the machining process has stringent requirements to obtain a precise size, accurate shape and strict surface integrity. The inclination angle changes during the curved surface milling process, owing to changes in the surface normal vector, thus affecting the surface quality.

In machining a complex curved surface, recent studies have mainly focused on the generation of a free-form surface method [12, 13], cutter path generation method for a free-form surface [14, 15], and interference discrimination of a tool and machining surface [16]. However, those studies did not consider the complexity of the free-form surface during CNC machining, which leads to use the processing experience or the test results to evaluate curved surface machining strategies in the actual processing [17].

Various studies on the surface quality during ball end milling of curved surfaces that considered different cutter path orientations have been conducted. Zhou et al. [18] have discussed the complex curved surface design technology, machining technology, and machining equipment, they predicted the development trend of complex curved surfaces. Lasemi et al. [19] have summarized the CNC machining of a free-form surface; described the generation of cutter paths, the identification of tool orientations and the selection of tool parameters; and discussed the problems that occur during free-form surface machining and future research directions. Lavernhe et al. [20] have established a three-dimensional morphology prediction model of a free-form surface and have studied the effects of the inclination angle on the surface morphology by using a prediction model and via milling experiments. Xie et al. [21] have focused on the unpredictable problem for the CNC machining of a complex free-form surface, have proposed a curvature distribution value to evaluate the CNC machining efficiency and machining precision, and have verified the validity by conducting experiments and analysis. Scandiffio et al. [22] have analysed the cutter path orientation and the contact area between the tool and the workpiece when machining tool steel and have summarized the cutting force, surface roughness, tool wear and tool life after machining cylindrical surfaces and inclined planes with different angles. de Souza et al. [23] have focused on the free-form surface milling process of tool steel, analysed the contact area between the tool and workpiece, and investigated the influence of cutting speed on cutting force, surface quality and chip generation. Durakbasa et al. [24] have evaluated the effects of milling and grinding on the surface roughness of a spherical surface and have demonstrated that the surface roughness after grinding ranges from 200 to 250 nm.

In conclusion, a group of researchers have focused on the effects of tool orientation on surface integrity and the CNC machining of curved surfaces and have obtained numerous research findings from the perspective of theory and experimentation. In the case of the TC17 titanium alloy, which is a difficult-to-machine material used for machining aero-engine blades, Tan et al. [25, 26] have investigated the effect of cutter path orientation on cutting forces, tool wear, and surface integrity in ball end milling of TC17, and Yang et al. [27] studied the tool rotational angle and inclination angle on surface integrity of TC17 barely. But, their milling specimens are flat, and their results will not be exactly the same as the curvature surface structure. In this paper, the effects of tool orientations and surface curvature on surface integrity experimentally during the finishing milling of TC17 titanium alloy were studied, and the different curvature surface structures were taken. The obtained results can provide guidance for the machining of complex curved surface parts of TC17 titanium alloy to obtain good surface integrity.

2 Milling process of TC17 titanium alloy

2.1 Definition of tool orientation and experimental model of curved surfaces

A ball end mill is widely used to produce complex curved surfaces, and there are various possible tool orientations for a certain cutter path, owing to its geometrical features. The lead angle and the tilt angle are often used to describe the tool orientation during the actual numerical control programming and post-processing. This paper adopts the rotational angle and the inclination angle to describe the tool orientation for the convenience of description and analysis. Figure 1a presents the analytical diagram of the tool orientation, and the conversion relationship between two sets of angles is as follows:

$$\begin{aligned}\beta_f &= \arctan(\tan\beta\cdot\cos\theta)\\ \beta_n &= \arctan(\tan\beta\cdot\sin\theta)\end{aligned} \quad (1)$$

where β_f: the lead angle; β_n: the tilt angle; β: the inclination angle and θ: the rotational angle.

Variation in the inclination angle can have a significant effect on the tool contact position; Fig. 1b shows a schematic view. R represents the tool radius, β denotes the inclination angle, a_p is the cutting depth, and η is the normal angle between the tool contact boundary and the cutting plane. The value of η can be calculated by solving Eq. (2):

$$\eta = ar\cos\left(\left(R-a_p\right)/R\right). \quad (2)$$

Clearly, the point with the highest cutting speed is close to the side edge of the tool. Using v_{max} as the linear velocity of the point, through a geometrical relationship, the following conclusion can be obtained: when the material is on the left side of the cutting tool, the tool centre does not participate in the milling process when $\beta-\eta>0^\circ$, and the minimum cutting speed $v_l = v_{max}\times\sin(\beta-\eta)$ (point E); when the material is on the right side of the cutting tool, if $\beta+\eta<90^\circ$, then the side edge is not involved in the milling process, and the maximum cutting speed $v_h = v_{max}\times\sin(\beta+\eta)$ (point G); the cutting speed of the maximum cutting depth $v = v_{max}\times\sin\beta$ (point F).

Surfaces can be divided into flat convex surfaces, flat concave surfaces, steep convex surfaces, and steep concave surfaces according to their characteristics. The blade surface includes numerous features such as the suction surface, the pressure surface, and the leading and trailing edge surfaces. According to the characteristics of the blade surface, for leading and trailing edge features, the change in the curvature is relatively large, and the curved surface is quite steep. To simulate the features, two different parabolas are chosen for the steep surface models; the mathematical equation of a parabola is $y^2 = 2px$, where the parameter p equals 0.5 and 2, representing the two types of convex surface models (denoted as K1 and K2). The curvature of the K1 convex surface ranges from 0.002~1, and the maximum is obtained at the top point. For the K2 surface, the range of the curvature was 0.025~0.25. The values indicate that the K1 surface is much steeper than the K2 surface. The blade body surface is usually the same as the flat curved surface, either the flat convex surface model, denoted K3, or the flat concave surface model, denoted K4. Three-dimensional models of the specimens are shown in Fig. 2. In the machining process of curved surfaces, variation in the normal vector leads to variation of the tool orientation, which in turn affects the surface integrity. The experimental studies of the blade characteristics were carried out according to the models. During the milling experiment, the cutting start points are shown in the models, and the length of the surface was measured from the start point along the feed direction in this paper.

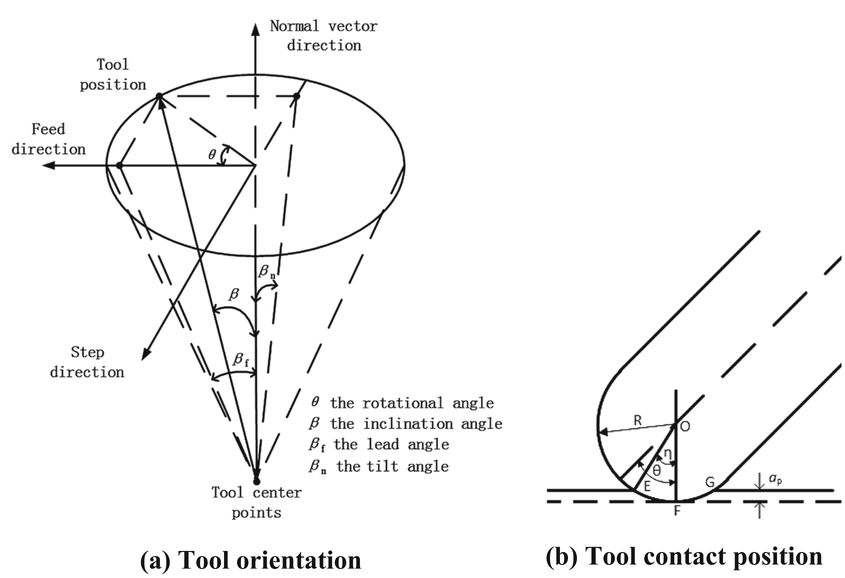


Fig. 1 Analytical diagrams of tool orientation and tool contact position. **a** Tool orientation. **b** Tool contact position

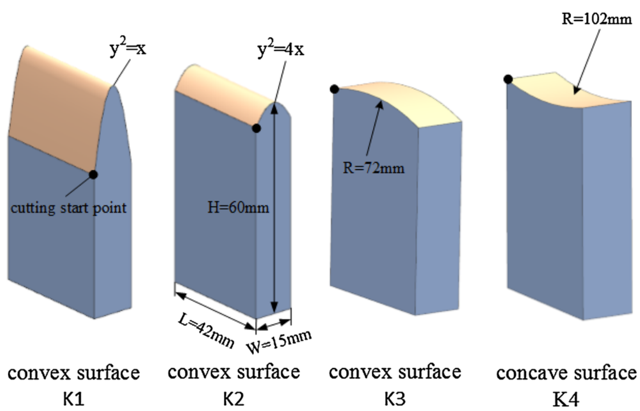


Fig. 2 Three-dimensional models of the specimens

2.2 Materials and tools

The workpiece material used was the TC17 titanium alloy; its chemical composition and main mechanical and physical properties at room temperature are given in Table 1 and Table 2, respectively. The shape of the workpiece for the tool orientation experiments was a rectangular block; the curved surfaces had the same shapes as those in the models presented above.

The experiment adopted a four-tooth K40 carbide ball end mill with a diameter of 7 mm, rake angle of 3°, first clearance angle of 10°, second clearance angle of 25°, and spiral angle of 40°.

2.3 Experimental procedure and test technology

The purpose of the tool orientation experiments was to study the effects of different tool orientations on surface integrity. Here, the single factor test was used in the experiments, and the rotational angle and the inclination angle were changed to explore the effect of each on the surface integrity. The first set of experiments initially used an inclination angle of 30°, and then the rotational angle was changed according to Table 3 in turns. The second set of experiments used rotational angles of 30° and 60°, and the inclination angle was changed in accordance with Table 4. The rotational angle with respect to the tool orientation was calculated in the clockwise direction, and the inclination angle was calculated as the angle between the cutting tool and the workpiece surface.

Regarding the K1 and K2 curved surfaces, taking the actual machining process scheme and a severe change in the curvature into consideration, here, two cutter path orientations were adopted. The first one was a vertical cutter path, in which the feed direction changed as the cutter travelled along the parabolas, i.e., the cutting process of the first half was vertical upward, whereas that of the second half was vertical downward. The second was a horizontal cutter path, in which the feed direction was horizontal along the ruled surface direction. The K3 and K4 surfaces adopted the vertical cutter path only because the change in the curvature was smooth. In addition, the cutter path orientations of the four curved surfaces are shown in Fig. 3.

The lengths of the K1, K2, K3 and K4 surfaces were 61, 25, 43 and 42 mm, respectively, as measured from the start points along the vertical feed direction. The inclination angle ranges of the K1, K2, K3 and K4 surfaces were 0~80°, 0~62°, 0~20° and 0~12°, respectively, on the basis of the model analysis, and the rotational angle remained unchanged during vertical machining. For the convex curved surfaces, the inclination angle decreased when the cutter path orientation was vertical upward and increased when it was vertical downward. The opposite was true for the concave curved surface.

All machining experiments were performed on a MIKRON UCP 1350, with a maximum power of 24 kW and a maximum spindle speed of 15,000 rpm. According to the empirical parameters in machining TC17, the cutting parameters adopted were as follows: spindle speed n = 5000 r/min (the cutting speed was 110 m/min), feed per tooth f_z = 0.06 mm/z, axial cutting depth a_p = 0.3 mm and cutting width a_e = 0.35 mm. In addition, the cutting condition was emulsion lubrication for all experiments. The length of the tool overhang was fixed at 40 mm to avoid the effects of different lengths on the test results.

The arithmetic mean roughness (Ra) was measured along the feed direction and the step direction by using a TA620 surface roughness tester (sampling length of 0.8 mm, assessing length of 5.6 mm), and the value was obtained by averaging five measurements. The surface morphology was measured by using an Austrian Alicona automatic tool measuring instrument, the amplification multiple was 50, and the resolution was 736 × 480 during the measurement process.

Table 1 Chemical composition of TC17 titanium alloy (wt%)

Al	Sn	Zr	Mo	Cr	Ti
4.5–5.5	1.6–2.4	1.6–2.4	3.5–4.5	3.5–4.5	Bal.

Table 2 Main mechanical and physical properties of TC17 titanium alloy

Tensile strength (MPa)	Yield strength (MPa)	Elastic modulus (GPa)	Elongation (%)	Density (g/cm^3)
1120	1030	112	10	4.68

Table 3 Variation in the rotational angle when the inclination angle is fixed

Inclination angle (β)	30°					
Rotational angle (θ)	0°	30°	60°	270°	300°	330°

Table 4 Variation in the inclination angle when the rotational angle is fixed

Rotational angle (θ)	Inclination angle (β)					
30°	0°	15°	30°	45°	60°	75°
60°	12°	24°	36°	48°	60°	72°

Residual stress was determined using the X-ray diffraction method. The PROTO LXRD MG2000 residual stress test and analysis system was used to measure the residual stress along the feed direction and the step direction, respectively. The aperture area was Φ2 mm for the tool orientation experiments and 2 × 4 mm for the curved surface experiments, owing to the severe change in curvature of the steep convex surface.

3 Results and discussion

3.1 Surface roughness

3.1.1 Surface roughness for different tool orientations

The relationship between surface roughness and the rotational angle is shown in Fig. 4a. Clearly, the surface roughness in the step direction was much higher than that in the feed direction. At the same time, the resulting roughness was better or presented a decreasing trend when the rotational angle was 0°~90° and 270°~360°. The main reasons for the surface roughness changing with the rotational angle are as follows:

The first is the variation of the cutting speed caused by the change in the rotational angle. When the rotational angle was 0°~90°, the linear velocity at the contact point was relatively high (average linear velocity $v \approx 72.5$ m/min). With the increase in the rotational angle, the linear velocity of the contact area was decreased. Increasing the cutting speed was helpful to improve the temperature of the contact area, soften the material, and decrease the friction coefficient. In addition, a higher speed may decrease the generation of built-up edge, scales and plastic deformation, thus resulting in a lower roughness. The second is the variation in the milling method. The analysis showed that the machining process was in the down milling state when the rotational angle was 0°~90° but in the up-milling state when the rotational angle was 180°~270°. The contact effect between the tool and machined surface aggravated the degree of cold hardening of the surface during the up milling process, thus decreasing the surface quality and resulting in a higher surface roughness.

Figure 4b shows the relationship between surface roughness and the inclination angle. The results indicated that the surface roughness along the step direction was more sensitive to changes in the inclination angle. In addition, an inclination angle too big or too small lead to a high surface roughness. The reason for this finding was that the cutting contact point was close to the tool centre when the inclination angle was too small, thus resulting in a smaller cutting speed, severe scraping and squeezing between the tool and the workpiece. Moreover, vibration of the machining system and tool deflection distortion are caused when the inclination angle is too large, thereby producing the high surface roughness.

3.1.2 Surface roughness for curved surfaces

For the K1 and K2 steep curved surfaces, the surface roughness along the ruled surface direction was measured throughout the experiments; hence, the roughness in the feed direction when using the horizontal cutter path and that in the step

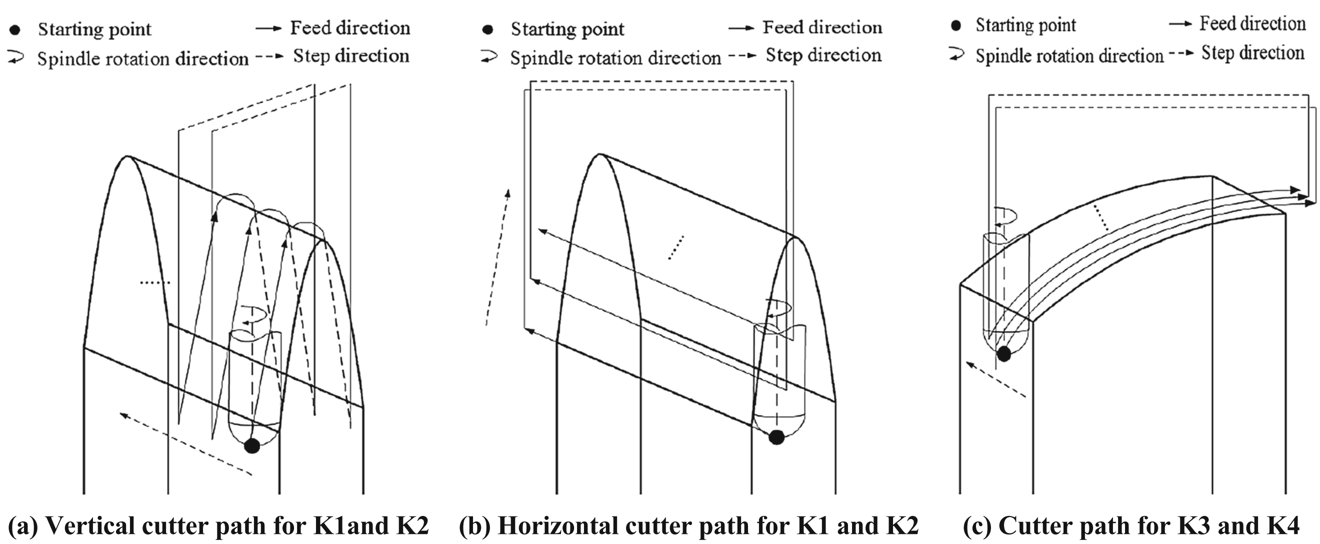
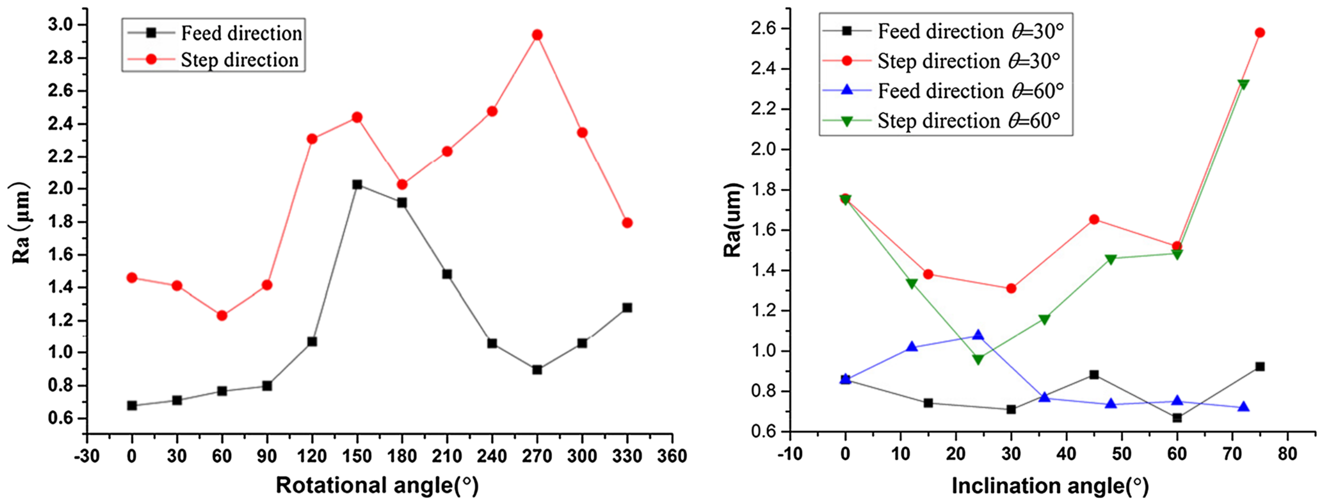


Fig. 3 Cutter path orientation for curved surfaces. **a** Vertical cutter path for K1 and K2. **b** Horizontal cutter path for K1 and K2. **c** Cutter path for K3 and K4



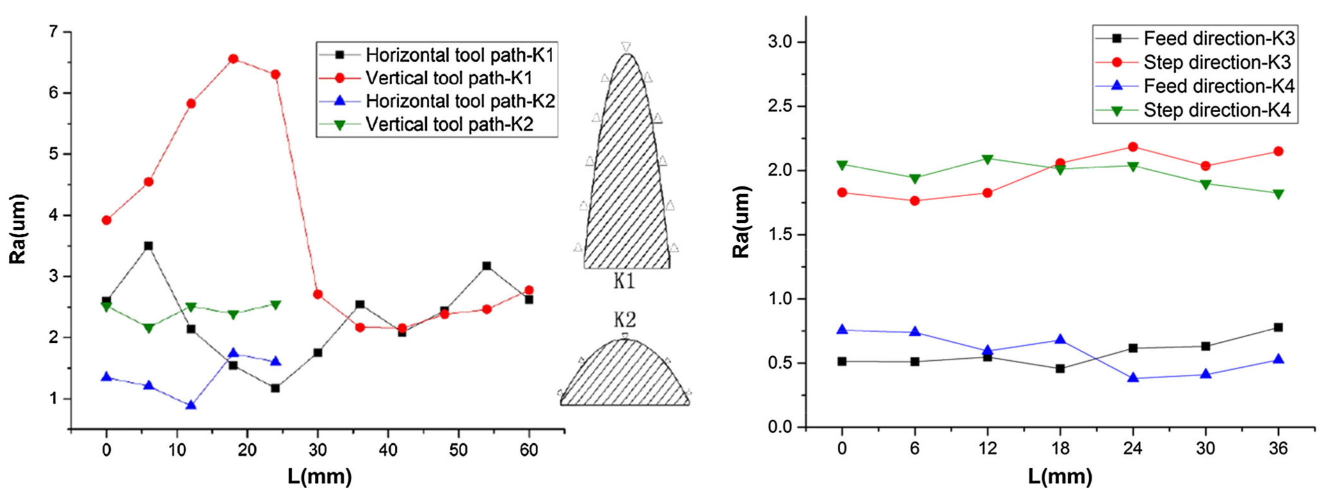
(a) The rotational angle (θ) **(b) The inclination angle (β)**

Fig. 4 Relationship between surface roughness and the tool orientation. **a** The rotational angle (θ). **b** The inclination angle (β)

direction when using the vertical cutter path was measured. The surface roughness distributed along the parabola of the K1 and K2 surfaces is shown in Fig. 5a. Moreover, the curvature along the parabola varied from 0.002 to 1 and reached a maximum value at the top position for K1, whereas it varied from 0.025 to 0.25 for K2; thus, the relationship between the curvature and surface roughness was also described. From Fig. 5a, the surface roughness when the cutter path orientation was vertical upward was higher than that when it was vertical downward for the K1 steep curved surface. In addition, for the K2 steep curved surface, the surface roughness changed slightly regardless of the cutter path used. The surface roughness was always low for the K1 and K2 steep curved surfaces when a horizontal cutter path was adopted.

For the K3 and K4 flat curved surfaces, the surface roughness at 7 points uniformly distributed in the feed direction on the curved surface was measured in both directions. The surface roughness distribution is shown in Fig. 5b. Clearly, the surface roughness in two directions was relatively stable for flat curved surfaces in fixed axis machining, possibly because the inclination angle was within a range of 20° for flat curved surfaces and changed slowly, thus resulting in the machining process being smooth. Moreover, vertical upward and downward cutting orientations had little effect on the roughness, and the roughness in the feed direction was lower than that in the step direction.

The change in curvature was equal to the change in the inclination angle during the machining process of curved surfaces. Therefore, the levels of surface roughness produced by the change in inclination angle were compared. Because the rotational angle was kept at 30° in the curved surfaces experiments, the roughness of the flat surfaces was analysed when



(a) K1 and K2 steep curved surfaces **(b) K3 and K4 flat curved surfaces**

Fig. 5 Surface roughness for curved surfaces. **a** K1 and K2 steep curved surfaces. **b** K3 and K4 flat curved surfaces

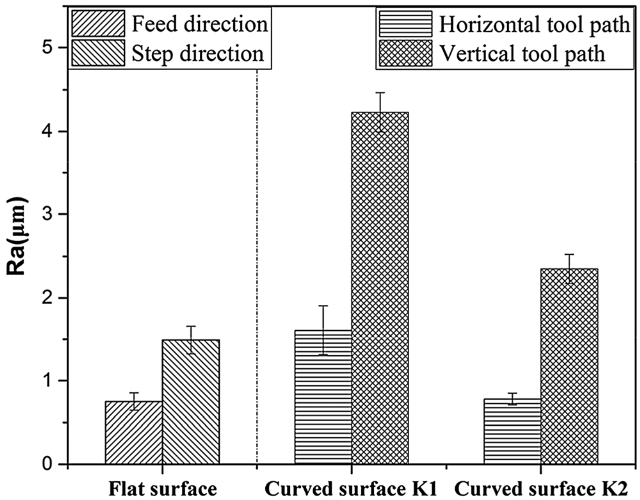


Fig. 6 Comparison of the surface roughness between flat and curved surfaces

the rotational angle was 30°. For flat surfaces with a rotational angle of 30°, the range of the surface roughness (*R*a) was 1.31~2.58 μm along the step direction, and the amplitude of variation was 1.27 μm. For the K1 steep curved surface, the range of the surface roughness (*R*a) was 1.17~3.51 μm and 2.16~6.56 μm when two cutter path orientations were used, and the amplitude of variation was 2.34 and 4.4 μm. For the K2 curved surface, the range of the surface roughness (*R*a) was 0.88~1.74 μm and 2.15~2.55 μm when two cutter path orientations were used, and the amplitude of variation was 0.86 and 0.4 μm. For the K3 and K4 surfaces, the surface roughness was stable, owing to the change in curvature being small, and the maximum amplitude of variation was 0.41 μm.

Figure 6 shows a comparison of the *R*a values when the inclination angle was in the range of 30°~60°, which was chosen because better surface roughness can be obtained in this range. Because the inclination angles of the K3 and K4 surfaces were within a range of 20° and the surface roughness was relatively stable, these two surfaces were not analysed here. Compared with that of the flat surface, the mean roughness of the curved surfaces was higher. The surface roughness fluctuation of K1 was obvious, possibly because the machining system can easily produce vibrations, owing to the large change in the curvature. Moreover, a better roughness can be obtained in the selected range of inclination angles for flat or curved surfaces.

3.2 Surface morphology

3.2.1 Surface morphology for different tool orientations

Partial results of the first set of experiments are shown in Fig. 7a–c. Variation in the rotational angle had a significant impact on the surface morphology. The texture direction of tool marks was consistent with the feed or step direction when the lead angle or tilt angle was 0°. In the intermediate states of four typical tool orientations, there a certain angle between tool marks and both directions (feed direction and step direction), resulted in the formation of various morphologies for different tool orientations.

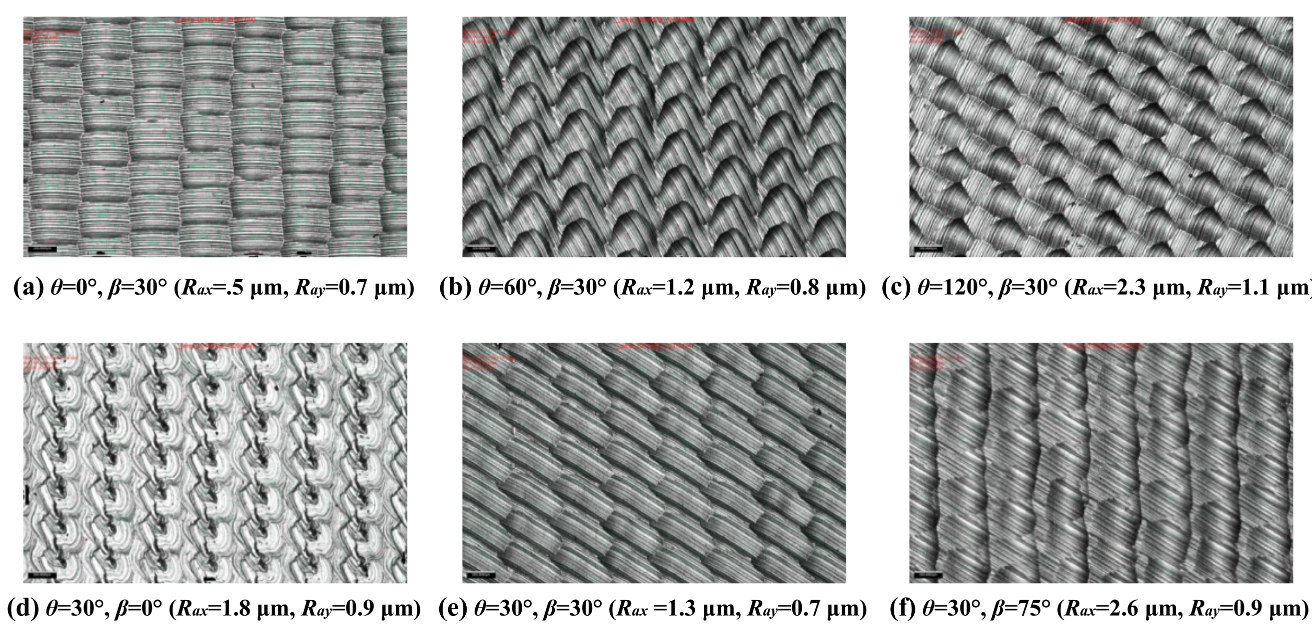


Fig. 7 Surface morphologies when changing the tool orientation. **a** θ = 0°, β = 30° (R_{ax} = .5 μm, R_{ay} = 0.7 μm); **b** θ = 60°, β = 30° (R_{ax} = 1.2 μm, R_{ay} = 0.8 μm); **c** θ = 120°, β = 30° (R_{ax} = 2.3 μm, R_{ay} = 1.1 μm); **d** θ = 30°, β = 0° (R_{ax} = 1.8 μm, R_{ay} = 0.9 μm); **e** θ = 30°, β = 30° (R_{ax} = 1.3 μm, R_{ay} = 0.7 μm); **f** θ = 30°, β = 75° (R_{ax} = 2.6 μm, R_{ay} = 0.9 μm)

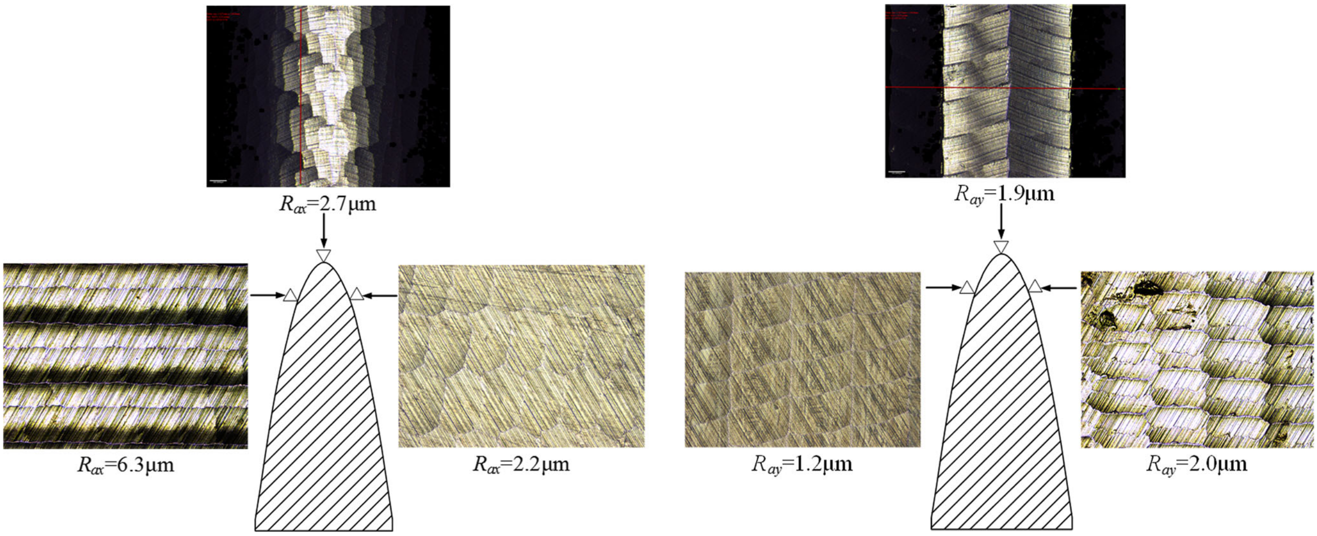


Fig. 8 Surface morphologies for the K1 steep curved surface. **a** Vertical cutter path. **b** Horizontal cutter path

Partial results of the second set of experiments are shown in Fig. 7d–f. The tool axis was parallel to the normal direction of the machined surface when the inclination angle was 0°, and the cutting speed in the contact area was zero, thus resulting in severe scraping and squeezing, significant plastic deformation on the surface and high surface roughness, as shown in Fig. 7d; these negative phenomena disappeared when the inclination angle was increased. However, the uniformity of the machined surface significantly deteriorated if the inclination angle reached 60° or more, possibly because the cutting force component in the vertical direction of the tool axis was increasing and deflection distortion of the cutting tool occurred, thereby affecting the surface quality. As shown in Fig. 7f, the maximum surface roughness was in the step direction, and the value was R_a = 2.6 μm.

3.2.2 Surface morphologies of curved surfaces

For the four different curved surfaces, several positions were selected, and the surface morphologies were measured. The morphologies of the K1 steep curved surface are shown in Fig. 8. The results indicated that the surface morphologies varied as the surface normal vector and the cutter path orientation changed. This result was equivalent to the change of rotational angle and inclination angle. In general, the surface morphology of the horizontal cutter path was flat, owing to the tool orientation being unchanged during each feeding time. The inclination angle changed from large to small and then increased when the vertical cutter path was used; here, the severe scraping phenomenon occurred on the surface for the vertical upward orientation, thus leading to a poor morphology.

For the K2 steep curved surface, the morphologies of the two cutter path orientations are shown in Fig. 9. The inclination angle was in the range of 0°~62° during the machining process of the K2 surface; because the change in curvature of the top position was large, the range of the angle on both sides was approximately 30°~60°. This was clearly a better range, on the basis of the tool orientation analysis; thus, a better milling morphology was obtained. The results indicated that

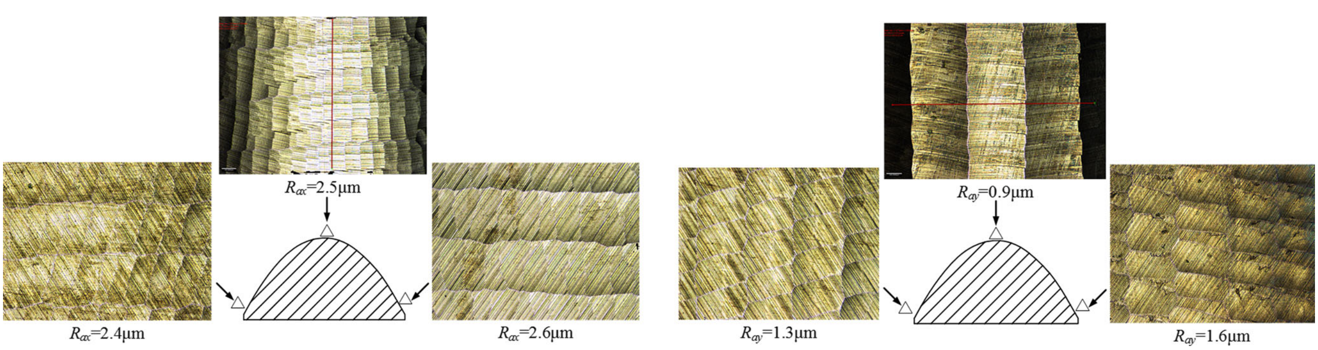


Fig. 9 Surface morphologies for the K2 steep curved surface. **a** Vertical cutter path. **b** Horizontal cutter path

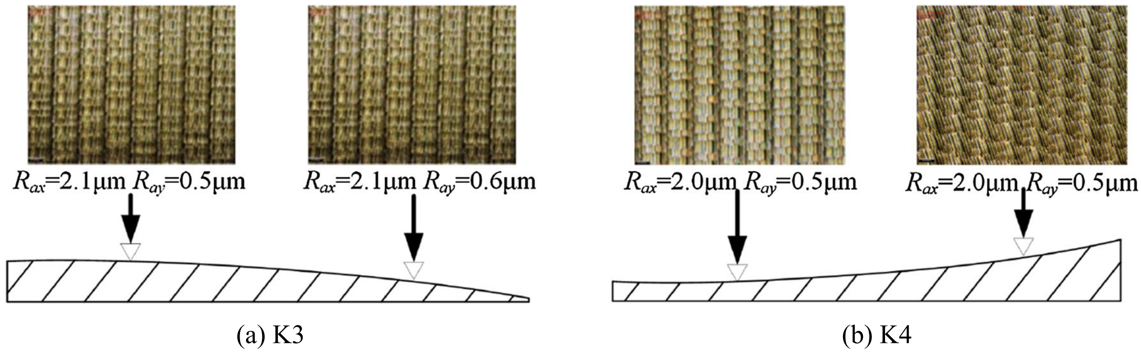


Fig. 10 Surface morphologies for the K3 and K4 flat curved surfaces. **a** K3. **b** K4

the surface morphology for a horizontal cutter path is smoother than that for a vertical cutter path, and there is little effect on the morphology regardless whether the orientation is vertical upward or downward.

Figure 10 shows the morphologies of the K3 and K4 flat curved surfaces. The surface morphologies of the flat curved surfaces were smoother than those of the steep curved surfaces, on the basis of the test results. In addition, there was no clear effect on the morphology regardless whether the orientation was vertical upward or downward, possibly because the change in the inclination angle for a flat curved surface was slow and the machining process was relatively stable, thereby resulting in a smooth morphology.

The surface morphologies were relatively smooth in the machining process of flat surfaces. Compared with the flat surfaces, the surface morphologies of the K1 and K2 steep surfaces were much rougher, possibly because the tool orientation changed rapidly during the machining process; thus, the system was prone to vibration. Moreover, the curvature change of the K2 surface was smaller than that of K1; thus, the morphology of the K2 surface was smoother than that of K1. For the K3 and K4 flat surfaces, the surface morphologies were smooth when the change in curvature was small.

3.3 Residual stress

3.3.1 Residual stress for different tool orientations

The relationship between residual stress and the rotational angle is shown in Fig. 11a. The results indicated that compressive residual stress was detected on all machined surfaces and that the variation of the rotational angle changed the value of the residual stress but not its properties. In addition, the residual stress had a similar tendency in both directions. Among them, the residual stresses in two directions had a similar tendency. A low residual stress value was obtained when the rotational angle was 0° and 180° (tool orientations *a* and *c*, respectively); a large value is obtained when the rotational angle was 90° and 270° (tool orientations *b* and *d*, respectively).

Figure 11b shows the relationship between residual stress and the inclination angle. There was considerable compressive residual stress on the workpiece surface when the inclination

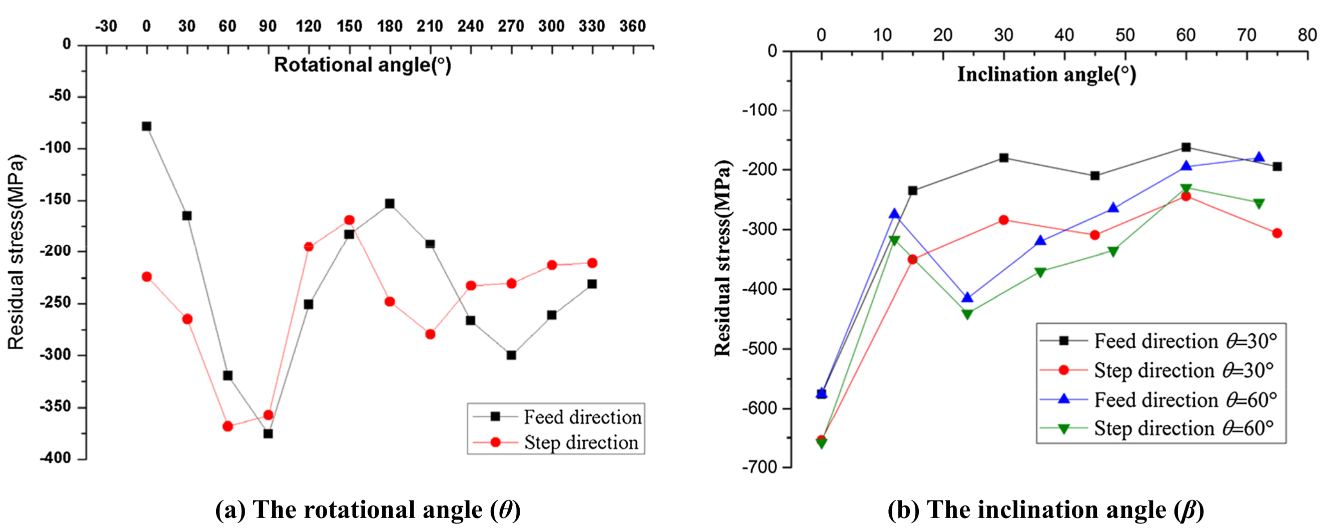


Fig. 11 Relationship between residual stress and tool orientation. **a** The rotational angle (θ). **b** The inclination angle (β)

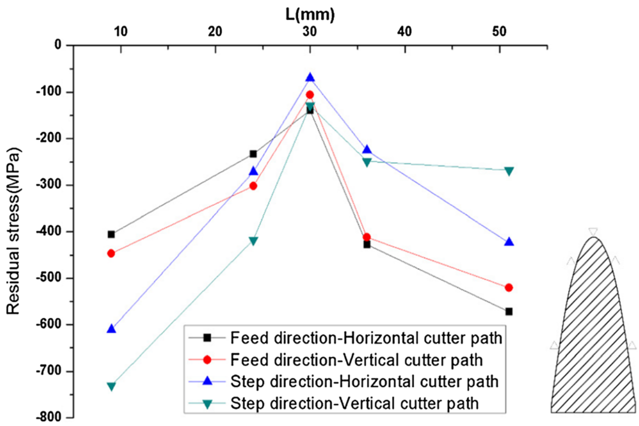


Fig. 12 Residual stress distribution for the K1 curved surface

angle was 0° (i.e., when the cutting tool was perpendicular to the workpiece surface) because the tool centre point was involved in the machining process and the cutting speed was zero, thus leading to severe friction and extrusion. The value of the residual stress decreased rapidly and then levelled off as the inclination angle increased. This result indicated that an increase in the inclination angle leads to a decrease in the residual stress.

3.3.2 Residual stress for curved surfaces

The length of the curved surfaces was calculated starting from the cutting start point, and the residual stress distributed along the parabola was measured. For the K1 steep curved surface, the residual stress distribution in two directions of the two cutter path orientations was as shown in Fig. 12, and the measurement positions are shown in the model. Overall, a large residual stress was obtained in the initial cutting stage and the eventual stage, whereas the minimum residual stress was detected at the top position. The residual stress had a similar tendency, and according to the comparison of the residual stress in two directions, there was no obvious effect of the cutting path orientation on the residual stress.

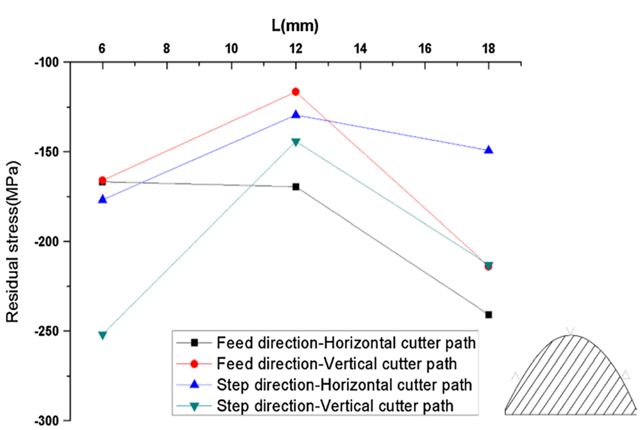


Fig. 13 Residual stress distribution for the K2 curved surface

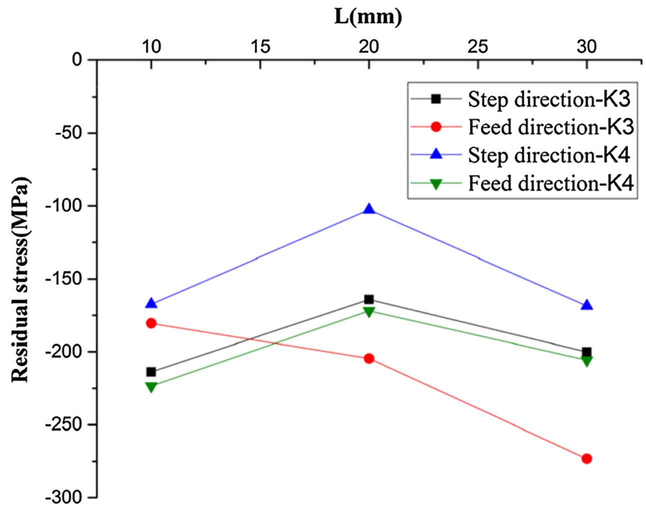


Fig. 14 Residual stress distribution for K3 and K4

During the machining process of the K1 curved surface, the inclination angle decreased when the vertical upward orientation was used, and the residual stress decreased correspondingly. The opposite was true when the vertical downward orientation was used. The largest residual stress was detected on the milling flat surface when the inclination angle was 0°, on the basis of the tool orientation analysis above, whereas the opposite was true for curved surfaces, owing to the inclination angle being theoretically 0° only at the highest point of the model, and the inclination angle changing drastically. However, the aperture area of the residual stress measurement for a curved surface was 2×4 mm, which led to the aperture area including not only the area with an inclination angle of 0° but also that within a range of approximately 30°, thus resulting in the residual stress of the top point not being maximal. This finding verified the results of the tool orientation experiments.

For the K2 steep curved surface, the residual stress distribution in two directions of the two cutter path orientations is

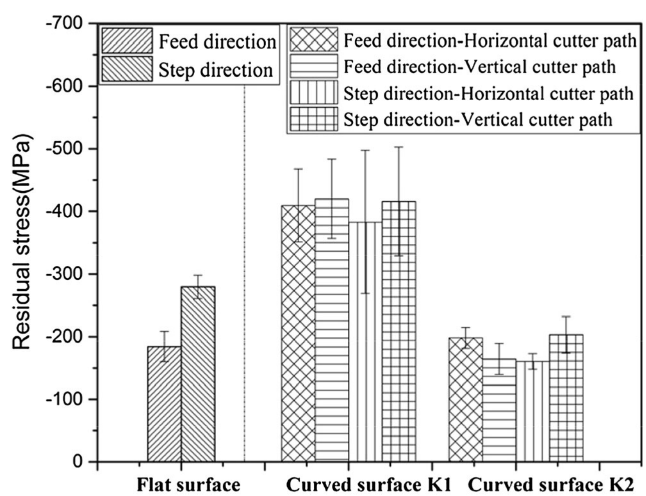


Fig. 15 Comparison of residual stress between flat and curved surfaces

shown in Fig. 13. Because the change in the curvature of the K2 surface occurred more slowly than that for K1, the variation of the inclination angle was less than that of K1 during the machining process. Therefore, the residual stress changed smoothly and the value was less than that of K1 surface. The results indicated that there was no obvious effect of cutting path orientation on the residual stress. Figure 14 shows the distribution of residual stress on the flat curved surfaces. The results revealed that for the flat curved surfaces, owing to the small range and the slow variation of the inclination angle, the residual stress showed no obvious change.

As for the analytical method of surface roughness, the residual stress of a flat surface with a rotational angle of 30° and that of the K1 and K2 curved surfaces were analysed. Figure 15 shows the comparison of residual stress when the inclination angle ranged from 30°~60°. A large residual stress was obtained when machining steep curved surfaces, and there was no obvious effect of cutter path orientation on residual stress. The figure shows that the mean compressive residual stress was less than −300 MPa and underwent a small fluctuation for the flat surface. Compared with that of the flat surface, the mean residual stress of the K1 curved surface was larger; the surface roughness fluctuation of K1 was apparent, and the compressive residual stress reached −420 MPa. For the K2 curved surface, the maximum surface compressive residual stress was less than −200 MPa and underwent a small fluctuation.

4 Conclusions

This article focused on the milling process of the TC17 titanium alloy and studied the influence of tool orientation on surface integrity for flat surfaces. On this basis, the conclusion was applied to the curved surface machining process, and the cutter path orientation was studied simultaneously. The results can be summarized as follows:

(1). The tool orientation had a large influence on the surface roughness, surface morphology and residual stress. The best surface integrity was obtained when the rotational angle ranged from 0°~90° and the inclination angle ranged from 30°~60° according to the test results.

(2). For curved surface machining, the surface roughness due to the vertical upward orientation was larger than that due to the vertical downward orientation when a vertical cutter path was used for four curved surfaces. For steep curved surfaces, the surface roughness and surface morphology produced for a horizontal cutter path were better than those for a vertical cutter path, and there was no obvious effect of cutting path orientation on residual stress. For flat curved surfaces, owing to the small range and the slow variation of the curvature, the residual stress showed no obvious change. In addition, the surface integrity of flat surfaces and curved surfaces was compared.

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