Study of Different Micro Milling Blades on Milling Titanium Alloy TC4

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Abstract. With the development of micro-miniature, micro-milling technology has been widely used. Due to the difference in workpiece materials and processing technology, the selection of the edge structure of the micro-milling cutter during processing is particularly important. This paper analyzes the influence of micro-milling of titanium alloy TC4 on cutting force, cutting heat and tool stress distribution for micro-milling cutters with a diameter of 0.1mm based on Definite-3D, ANSYS and other finite element simulation software. The results show that the spiral-edge micro-milling cutter can effectively reduce the cutting force and cutting heat compared with the straight-blade micro-milling cutter. Considering the rigidity, strength, cutting performance and practicability of the tool, the traditional double-edged spiral-edge micro-milling is still the best choice. The research results of this paper can provide a theoretical basis for the design of micro-milling tools.

1. Introduction

With the continuous development of science and technology, the demand for micro-featured parts in the defense, military, aerospace, medical equipment and other manufacturing fields has increased significantly. Due to the high efficiency, high flexibility, high aspect ratio structure of micro-milling technology, micro-milling Tool technology has become a research hotspot in the field of micromachining [1-3]. Due to the small diameter and low rigidity of the micro-milling cutter, the overall rigidity of the tool is usually increased as much as possible in the tool design. Due to the different processing techniques and parts requirements, domestic and foreign scholars have developed a variety of micro-milling cutters with different blade structures. Asma Perveen [4] et al. used EDM to fabricate a micro-milling cutter with a V-groove and analyzed the effect of the shape of the cutting edge on the tool wear. It was found that the D-edge cutting tool has a triangular-to-square cutting tool. Better wear resistance. Uhlmann [5] et al. improved the rigidity of the tool by reducing the cutting length of the cutting edge and optimized the end mill with a diameter of 0.5 mm. Fang [6] et al. used finite element software to compare the structure of straight-blade triangle, D-shaped and pyramid-shaped micro-milling cutters with the traditional spiral end mill structure, and through a large number of experiments, from the tool stiffness, pointed out Cone D-shaped end mills are more suitable for micro-milling. Jiang et al. [7] optimized the spiral groove and edge shape of the end mill based on bionics, effectively suppressing the generation of serrated chips and reducing the fluctuation of cutting force. AURICH et al. [8] studied the design and sharpening of single-blade spiral micro-milling cutters,
and proved that the micro-milling cutter with spiral groove structure can significantly reduce the workpiece burr. Li P et al. [9] used the analytical modeling and finite element method to geometrically optimize the commercial end mill with a diameter of 0.5mm, increase the tool neck angle and adopt the negative rake angle structure to improve the rigidity and strength of the tool. Small tool wear and extended tool life.

As a typical difficult-to-machine material, titanium alloy TC4 has been widely used in the industrial field due to its excellent comprehensive properties such as high temperature resistance and corrosion resistance [10-11], due to the high speed of the micro-milling spindle and the small diameter of the milling cutter. In the processing of difficult-to-machine materials such as titanium alloy TC4, the phenomenon that the blade is broken is more likely to occur, which is not conducive to the experiment. Therefore, many scholars usually use plastics such as copper and aluminum alloy to study [12-13]. There are few studies on micro-milling titanium alloy TC4 materials.

Although domestic and foreign scholars have carried out a lot of research on micro-milling technology, they mainly focus on the preparation of micro-milling cutters [14-17], structural optimization design [18-20], etc., for the milling performance of many different edge-type micro-milling cutters. The comparative study is not sufficient. Due to the complicated milling movement, the micro-milling scale is very small, modeling is difficult, and considering the long manufacturing cycle and complicated process of micro-milling cutter, this paper analyzes the milling of titanium alloy TC4 with different edge-type micro-milling cutters by using finite element software such as DEFORM and ANSYS. The influence law of cutting force and cutting heat is applied. The modal analysis of micro-milling cutters with different edge shapes is carried out. The static and dynamic characteristics of the micro-milling cutters are studied, which provides a reference for the optimization of the edge shape of the micro-milling titanium alloy TC4.

2. Establishment of finite element simulation model

Finite element is currently the common method for simulating the cutting process of the tool. The commonly used finite element software for the simulation cutting process is abaqus, Ls-dyna, Deform-3D and AdvantEdge. Deform-3D has the advantages of good robustness, high calculation accuracy and high reliability. Therefore, this article uses Deform-3D as the simulation software. The simulation uses side milling, the tool material is YG6, and its physical performance parameters are shown in Table 1.

| Performance                  | Numerical value |
|------------------------------|-----------------|
| Density/(g/cm3)              | 14.6-15.0       |
| Bending strength/(MPa)       | 1450            |
| Hardness/(HRA)               | 89.5            |
| Impact toughness /(J/cm²)    | 2.6             |

The workpiece material is Ti-6Al-4V, and its physical property parameters are shown in Table 2.

| Performance                | Numerical value   |
|----------------------------|-------------------|
| Density/(g/cm3)            | 4.51              |
| Poisson's ratio            | 0.3               |
| Tensile strength/(MPa)     | 860               |
| Breaking strength /(MPa)   | 967               |
| Specific Heat Capacity /[J/(g·K)] | 0.61             |
| Coefficient of Linear Expansion /(K-1) | 8.6×10-6         |
| Elongation / (%)           | 8                 |

The workpiece material is Ti-6Al-4V, and its physical property parameters are shown in Table 2.
Through the solidworks software, the tool cutting edge section is Δ shape (a, g), D shape (b, n), rectangle (c, i), regular pentagon (d, j), regular hexagon (e, k) And the traditional double-edged spiral (f, l) straight edge, spiral edge two types of micro-milling geometry model, as shown in Figure 1. The established milling cutter and workpiece geometry model are imported into Deform-3D for pre-processing. The workpiece size is 0.1mm×0.05mm×0.1mm, the bottom surface of the workpiece is set to full constraint, and the tool rotates around the Y axis and feeds along the Z axis. In order to improve the simulation efficiency, the cutting edge length is set to 0.2mm. Table 3 shows the machining process parameters used in the simulation experiment. The established micro-milling model is shown in Figure 2.

![Figure 1: Different milling cutters](image1)

![Figure 2: Micro-milling model](image2)

| Process parameters       | Numerical value       |
|--------------------------|-----------------------|
| Spindle speed/(rpm)      | 40000, 45000, 50000, 55000, 60000 |
| Feed per tooth/(mm/tooth)| 0.005                 |
| Radial width of cut/(mm) | 0.005                 |
| Axial width of cut/(mm)  | 0.05                  |
| Initial temperature/(℃) | 20                    |

### Table 3. Processing parameters

3. Simulation result analysis

Single-factor experimental method was used to analyze the milling force and milling heat during the milling of titanium alloy TC4 under the same milling conditions for five different spindle speeds under
the conditions of 40000, 45000, 50000, 55000 and 60,000 rpm. Due to the data processing, it is found that the milling force and the cutting heat change trend of the micro-milling cutters with different blade structures are basically the same under different speed conditions. Therefore, the data in the figure are taken as the autonomous axis rotation speed $n=50000\text{r}$, and the results are analyzed as follows.

3.1 Analysis of cutting force

Figure 3. Comparison of milling force variation of straight edge micro-milling cutter

1. Traditional double-edged 2.D 3. $\triangle$ 4. Rectangle 5. Positive pentagon 6. Hexagon

Figure 4. Comparison of cutter milling force of Straight edge type micro-milling

Figure 3 shows the milling force variation curve of a straight edge type micro-milling cutter with different cutting edge sections in one milling cycle. It can be seen that the milling force is the same as the milling cutter edge during the milling process. With the increase of the increase, the micro-milling cutter with the traditional double-edged spiral edge section can obtain smaller milling force than the micro-milling cutter of other sections; and the moment of the maximum milling force increases with the number of teeth of the milling cutter. Gradually delayed, this is because the straight edge micro-milling cutter with $\triangle$ shape, rectangular shape, regular pentagon shape and regular hexagonal cross section can be regarded as negative rake angle cutting during milling, and the corresponding rake angle is $-30^\circ$, respectively. $45^\circ$, $-54^\circ$, $-60^\circ$, as the absolute value of the negative rake angle increases, the values of the radial force $F_x$ and the tangential force $F_z$ also gradually increase, and when the absolute value of the negative rake angle is greater than $54^\circ$ The direction force $F_x$ is gradually greater than the tangential force $F_z$, as shown in figure 4.
Figure 5. Comparison of milling force variation of spiral edge micro-milling cutter
1. Traditional double-edged 2. D 3. Δ 4. hexagon 5. Rectangle 6. Positive pentagon

Figure 6. Comparison of cutter milling force of Spiral Edge Micro-milling

Figure 5. shows the milling force variation curve of a helical edge type micro-milling cutter in one milling cycle. Compared with Figure 3, it can be seen that the milling force generated by the spiral-edge micro-milling cutter is smaller than that of the straight-blade type micro-milling. The knife is small, the minimum milling force is only about 0.4N, and the milling force increases first and then decreases with the increase of the number of milling cutters. The spiral blade micro-milling cutter with the regular pentagon edge section is compared. The maximum milling force is generated, and the maximum milling force generally occurs during the half of the milling cycle, at which point the tool is rotated by 45°, which is the moment when the cutting edge is completely cut. The milling force component of the spiral edge type micro-milling cutter is shown in Figure 6. The difference compared with the straight edge type is that the radial force Fx is always smaller than the tangential force Fz as the absolute value of the negative rake angle increases.

3.2 Analysis of cutting heat
During the metal cutting and forming process, the heat of cutting not only affects the service life of the tool, but also affects the stability of the machining process and destroys the surface quality of the workpiece. In general, the cutting heat is transmitted along with the cutting fluid and the chips. However, due to the particularity of the micro-milling process, the diameter of the micro-milling cutter is small, and the chip removal is difficult. The flow of the cutting fluid causes a certain impact on the tool, which leads to the tool. Breaking and other problems, so the cutting fluid is basically not allowed during processing. Therefore, it is especially important to select the right tool and match the correct processing parameters to effectively reduce the heat of cutting.

Through the analysis, the cutting temperature of the micro-milling cutter with different edge structures is changed with the shape of the cutting edge, as shown in Figure 7. It can be seen that: 1. The cutting temperature gradually increases with the increase of the number of edges, but the increasing range is gradually slower; 2. Under the same processing parameters, the traditional double-edged spiral micro-milling cutter can significantly reduce the cutting. Temperature, the temperature during cutting is 169.5 °C, far lower than the processing temperature of other types of tools. Compared with the spiral-edged tool, the straight-blade tool produces a higher cutting temperature during the machining process. The main reason is that the straight-blade cutter is the cutting edge and cuts into the workpiece at the same time, and the spiral-edge cutter is progressively cut into the workpiece, reducing The unit cutting force, and the existence of the spiral groove
improves the chip's chip and chip removal ability to a certain extent, thereby reducing the cutting temperature.

**Figure 7.** Milling temperature comparison of different edge type micro-milling

In general, the traditional double-edged spiral-edge structure micro-milling cutter can effectively reduce the cutting force and cutting temperature during cutting. Different tool edge shapes can be regarded as changes in the tool rake angle. As the rake angle increases, the cutting force and cutting temperature decrease continuously, but the larger the rake angle may reduce the overall rigidity of the tool, and the cutting edge is easier damaged. Therefore, changes in tool stiffness must also be considered in tool design.

### 3.3 Stress analysis

Due to the small diameter and low structural strength of the micro-milling cutter, it is easy to break during the micro-milling process. Therefore, the stress analysis of the structure of the micro-milling cutter must be carried out to investigate the deformation and stress variation of the micro-milling cutters with different cutting edge shapes. The edge shape optimization of the micro-milling cutter can be used for reference. Referring to the conventional double-edged spiral micro end mill with a diameter of 0.1mm, the cutting edge structure and the cutting edge section are shown in Figure 8. The structural parameters of the micro milling cutter holder are shown in Figure 8, and Table 4, and different blade structures are established. A three-dimensional model of a complete micro-milling cutter.

**Table 4.** Structure parameters

| D1 (mm) | D2 (mm) | L (mm) | L1 (mm) | L3 (mm) | \( \angle 1 \) (°) | \( \angle 2 \) (°) |
|---------|---------|--------|---------|---------|----------------|----------------|
| 0.1     | 4       | 50     | 0.2     | 10.5    | 15            | 15            |

The established micro-milling model is imported into the finite element software Ansys for static analysis. The tool overhang is set to 20mm. The overall structure of the tool is divided into three sections for mesh division. The head part (L2) has the smallest unit size and the grid is more Dense, can effectively improve simulation efficiency and accuracy. The surface loads are applied to the rake face of the micro-milling cutters with different edge structures to solve the displacement variation and the maximum stress value of the different milling cutters with different blade structures under the same external force load conditions.
As shown in Figure 9, the displacement variation and maximum stress of the micro-milling cutters with different cutting edge shapes can be seen. 1. The helical blade type micro-milling cutter has less deformation and stress than the straight-blade type. The maximum stress occurs at the end of the spiral groove of the cutting edge and the joint between the root of the cutter head and the neck, that is, the easy break point during the machining process, as indicated by the circle in Figure 10. 2. Compared with Fang et al. [6], the workpiece material is selected from brass, which has good plasticity. It is easier to process than titanium alloy TC4, and it adopts end milling mode, and its cutting amount is smaller. It is found through research that the stiffness and overall strength of the D-type tool are better than those of other edge-type structures under the same milling conditions, but it ignores the special structure of the D-type tool whose back angle is too small during the actual cutting process. It will increase the unnecessary contact between the flank and the machined surface, and the frictional force will increase, which will lead to the increase of cutting force and cutting heat, which may cause serious damage to the processed surface quality of the workpiece.

For the spiral cutter type micro-milling cutter, the stiffness and strength of the micro-milling cutter are not high. It is necessary to consider the cross-sectional shape of the cutting edge and the material removal rate of the cutter head. The main reason for the high rigidity of the multi-blade milling cutter may be due to the appropriate negative The front corner design retains a large amount of cutter head material, but this structure will inevitably lead to a decline in cutting performance, and considering the complexity of multi-blade micro-milling cutter manufacturing, the traditional double-edged spiral-edge micro-milling cutter is still the best choice.

4. Conclusion
Based on the finite element software such as DEFORM and ANSYS, the influence law of different edge type micro-milling cutters for milling titanium alloy TC4 and the modal analysis of micro-milling cutters with different edge types were analyzed. The following conclusions were drawn:

(1) The spiral-edge micro-milling cutter has better performance than the straight-blade micro-milling cutter in reducing the cutting force and the cutting heat. The traditional double-edged spiral-edge micro-milling cutter can produce the minimum cutting force and cutting heat during the machining process.

(2) The cutting temperature gradually increases with the increase of the number of edges, but the increasing range is gradually slower, indicating that when the number of edges reaches a certain node, the effect of increasing the number of edges on the cutting temperature rise is gradually weakened.
(3) Straight edge type and spiral edge type micro-milling cutters under the static load, a stress concentration area will appear at the end of the cutting edge and the joint between the neck and the shank, which is also the actual operation of the micro-milling cutter. The location where the fracture is most likely to occur during processing.

(4) In the case of the same tool diameter, although the traditional double-edged spiral-edge micro-milling cutter retains less material, resulting in low stiffness and overall strength, considering the cutting performance and practicality, the traditional double-edged spiral Blade-type micro-milling cutters are still the best choice.

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