Performance analysis of double-groove cutter based on ABAQUS numerical simulation

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Abstract. In order to study the influence of double-slotted cutter on chip forming, this paper uses the general finite element simulation software ABAQUS, and builds a finite element model based on Johnson-cook material model and Johnson-cook fracture criterion. This paper analyzes the changes in cutting force and cutting temperature obtained when cutting titanium alloys with three different double-slot structures. This paper draws the cutting force and cutting temperature change curve at the tool tip, and analyzes and compares the post-processing results of the three geometries. The test results show that the double concave arc groove cutter has less cutting force and cutting temperature during cutting, and the cutting process is relatively stable, which is more suitable for cutting than other groove types.

1. Introduction
Titanium alloy has good mechanical properties, high strength and low density, and also has excellent corrosion resistance and toughness. Therefore, titanium alloy is a new important material used in the aerospace industry [1]. However, the process performance of titanium alloy is not good, and the machining of titanium alloy is relatively difficult. Titanium alloys require a large cutting force during processing, and the cutting temperature is high, which is easy to cause problems such as work hardening, difficult chip breaking, and easy tool wear. The use of tools with chip breakers of reasonable structure in the rake face can improve chip breaking performance and improve the surface quality of the workpiece.

At present, there are few studies on double-groove chipbreaker cutters. Research at home and abroad mainly focuses on the geometric parameters of single-groove cutters and the influence of the three elements of cutting [2-3]. This paper adopts the Johnson-cook material constitutive model, and uses the finite element software ABAQUS to conduct thermal-mechanical coupling cutting simulation of three different groove-type combination tools, and study the effect of groove-type combination methods on cutting force and cutting temperature. The results of this study provide a basis for the combination of the tool geometry of the double-groove structure and the actual cutting process.

2. Basic theory and material model

2.1. Basic theory
When the metal is cut, the workpiece will undergo elastic-plastic deformation under the action of large strain and high temperature. The time from chip formation to detachment from the workpiece surface is very short, and the distribution of temperature, stress and strain rate at each node in each cutting layer presents an uneven change state [4]. Therefore, a reasonable constitutive model plays a vital role
in cutting simulation. The model must reflect the influence of strain, temperature and strain rate on the chip forming process.

The metal to be cut needs to undergo a process from elastic deformation to plastic deformation. The entire cutting process becomes very complicated due to high strain, high strain rate and high temperature. The Johnson-cook flow stress model is a cutting simulation model that comprehensively considers various factors. This model is more consistent with the actual situation, so it is widely used in the world [5]. The constitutive model is given by formula (1):

\[
\sigma_{eq} = (A + B \varepsilon_{eq}^n) \cdot (1 + C \ln \varepsilon^*_{eq}) \cdot (1 - T^*)^m
\]  

(1)

In the formula: \(\sigma_{eq}\) is the flow stress; \(\varepsilon_{eq}\) is the equivalent strain; In this formula, \(T^* = \frac{(T - T_f)}{(T_m - T_f)}\), \(T^*, T_m\) and \(T_r\) are the deformation temperature, melting point and room temperature of the workpiece; \(\varepsilon^*\) is the yield strength under quasi-static conditions; \(B\) is the hardness modulus; \(n\) is the strain hardening parameter; \(C\) and \(m\) are the strain strengthening parameter and thermal softening coefficient, respectively. The material constitutive parameters of titanium alloy Ti6Al4V are shown in Table 1. [6]

| A (Mpa) | B (Mpa) | C   | n    | m    |
|--------|--------|-----|------|------|
| 875    | 793    | 0.01| 0.386| 0.71 |

2.2. Material fracture criterion

This paper adopts the Johnson-cook failure criterion applicable to metals at high strain rates, let \(D_1^*\) be the failure parameter; \(p\) is the hydrostatic pressure; \(q\) is the equivalent stress; \(\varepsilon_0\) is the reference strain rate, the \(\varepsilon^\text{pl}_{f}\) on the left side of the equation is the equivalent strain at failure, \(\varepsilon^\text{pl}\) is the strain rate at failure. Specific expression such as formula (2):

\[
\varepsilon^\text{pl}_{f} = D_1 + D_2 e^{\frac{D_3}{\eta}} \cdot \left[1 + D_4 \ln \left(\frac{\varepsilon^\text{pl}}{\varepsilon_0}\right)\right] \cdot (1 + D_5)
\]  

(2)

The unit failure criterion parameters of Ti6Al4V material are shown in Table 2. [7]

| \(D_1\) | \(D_2\) | \(D_3\) | \(D_4\) | \(D_5\) |
|------|------|------|------|------|
| -0.99| 0.25 | -0.5 | 0.014| 3.87 |

2.3. Finite element geometric model

The double-groove structure chipbreaker is a composite groove type, which combines the first-level groove and the second-level groove in a certain size and manner, so that the groove type takes into account the advantages of the first and second-level grooves [8]. Although the composite insert is generated through simple geometry combination, the change of the combination and the optimization of structural parameters can improve the chip breaking performance of the insert while ensuring the service life of the cutter. This simulation experiment carried out simulation cutting on three grooves with double groove structure, and controlled the rake angle of the three grooves to be 35° and the relief angle to 10°. Compare the changes of the cutting force and cutting heat of the three grooves.

Three trough structures are shown in Figure 1.
This cutting simulates finishing cutting, so a smaller back-cutting amount of 0.2mm was selected, and the cutting speed was 300m/min. The material used for the cutting model workpiece is Ti6Al4V, and the cutter material is high-cobalt high-speed steel W2Mo9Cr4VC8. In the pre-processing stage, it is necessary to impose constraints on the workpiece to prevent the workpiece from sliding, and then select nodes on the cutter to apply speed load. During simulation, set the initial temperature of both the cutter and the workpiece to 20 °C. The cutting model is shown in Figure 2.

3. Finite element simulation results

Under the same cutting parameters, through the simulation cutting of three kinds of double groove structure chipbreaker cutters, the influence of different groove type combination methods on chip deformation is analyzed. The results are as follows:

3.1. Cutting test and analysis of double trapezoidal groove cutter

The stress cloud diagram of the double trapezoidal groove cutter is shown in Figure 3.
Figure 4. Double trapezoidal groove cutter post-processing.

It can be seen from Figures 3 and 4: (1) When the double trapezoidal groove cutter is cutting, the chip contact area is larger, the chip curling radius is larger, and the chips are not easy to break. (2) The X-axis direction is the main cutting force, and the main cutting force is stable and finally about 690N. The Y-axis direction is the feed cutting force, and the feed cutting force is stable at about 100N. The cutting process is relatively stable and the cutting force fluctuation is small. (3) The cutting temperature is stable at 330°C, the cutting temperature changes relatively smoothly and the fluctuation is small.

3.2. Cutting Test and Analysis of Double Concave Arc groove cutter

The stress cloud diagram of the double arc groove cutter is shown in Figure 5.

Figure 5. Stress cloud diagram of double concave arc groove cutter.

The stress cloud diagram of the double arc groove cutter is shown in Figure 6.
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(a) Cutting force. (b) Cutting temperature.

Figure 6. Double concave arc groove cutter post-processing.

It can be seen from Figures 5 and 6: (1) When cutting with a double-arc groove tool, due to the extrusion of the first-level groove, the chip deforms seriously, the chip curling radius is small, and the chip is easy to break. (2) The cutting force fluctuates to a certain extent, and the amplitude of the fluctuation is relatively small. The main cutting force is about 600N and fluctuates up and down with an amplitude of 100N. (3) The cutting temperature fluctuates slightly around 260°C.

3.3. Cutting test and analysis of straight-convex arc groove cutter
The stress cloud diagram of the straight-convex arc groove cutter is shown in Figure 7.

Figure 7. Stress cloud diagram of straight-convex arc groove cutter.

The post-processing of the cutting force and cutting temperature of the straight-convex arc groove tool is shown in Figure 8.
It can be seen from Figures 7 and 8 that: (1) The straight-convex arc groove cutter is different from the traditional concave curved straight circular groove. The groove back of the groove is changed to a convex elastic retaining ring. When cutting, the contact area of the chip on the rake face and the chip breaker is not large, and the curl radius of the chip is smaller, which makes the groove easier to break the chip compared to the traditional concave surface groove. (2) The main cutting force is unstable and fluctuates sharply at 800N, which may cause large machining errors on the machined surface. (3) The cutting temperature rises to violent fluctuations around 270 °C.

4. Conclusion

(1) This cutting simulation introduces and tests the cutting performance of three double-slot structure groove cutters. After analyzing the cutting force and cutting temperature, it is concluded that the cutting force of the double trapezoidal groove cutter is smaller and the cutting process is relatively stable, but Chip curl 7 has a large radius, poor chip breaking effect, high cutting temperature, and cutting heat is not dissipated in time with the chip falling off; the cutting force and cutting temperature of the double-concave arc groove tool are small, and the chip can also be timely breaking. Although there is a certain vibration during the cutting process, it is still acceptable. The linear-convex arc groove tool has a good chip breaking effect, but the cutting force is high and the fluctuation is the largest, which will affect the surface quality of the workpiece and the tool life of the tool influences.

(2) It can be seen from the turning test of the three-groove chipbreaker that the double-arc groove cutter guarantees the service life of the tool under the premise of meeting the chipbreaking requirements, and is the most suitable geometry for cutting. There are various combinations of different geometries, and the obtained chip breaking performance and mechanism are also different, which is worthy of in-depth study and exploration.

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