Three-dimensional finite element simulation of high speed milling of titanium alloy Ti6Al4V

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Abstract. In this paper, ABAQUS finite element simulation software was used to establish a more reliable three-dimensional milling titanium alloy Ti6Al4V finite element simulation model. This model sets up important links such as the material constitutive model, the tool-chip contact friction model, and the chip separation criterion. And the accuracy of the model is verified by experiments. Based on this model, orthogonal experiment was used to explore the effects of axial cutting depth, tool speed and feed speed on the milling force. And the morphology of the chip and the surface morphology of the machined workpiece were investigated. The results show that the influence of cutting parameters on milling force from high to low is as follows: axial cutting depth > tool speed > feed rate. The change of cutting parameters has different influence on milling force in all directions, and has the largest influence on milling force in X direction.

1. Introduction
Titanium alloy, as one of the high-strength materials in industry, has been widely used in military and aerospace fields due to its excellent characteristics such as high strength, high temperature resistance and corrosion resistance[1]. At the same time, the characteristics of titanium alloy, such as small deformation coefficient, low thermal conductivity and small elastic modulus[2], lead to a series of problems such as unable to timely discharge of cutting heat and serious tool wear during cutting, which make titanium alloy become a typical material difficult to machining[3]. In the process of milling, the change and magnitude of milling force have a significant effect on the machined surface integrity, tool wear and life. Accurate prediction of milling force has a positive guiding significance for optimizing the parameters such as feed speed and cutting amount when machining titanium alloy.

Many researches on the prediction of milling force have been carried out by scholars at home and abroad. Zhao[4] analyzed the cutting force in high-speed cutting of Ti6Al4V with different cutting dosage. Liu[5] carried out finite element simulation study on the influence of cutting amount on cutting force and cutting temperature in milling Ti6Al4V. Chen[6] established a three-dimensional finite element simulation model for the high-speed milling process of Ti6Al4V, and explored the influence rules of axial cutting depth, feed per tooth, radial cutting depth and cutting speed on the milling force. Wang[7] obtained through numerical simulation analysis that the cutting force, main cutting force and cutting depth resistance in the cutting process of titanium alloy all increased with the increase of radial cutting depth and axial cutting depth, and decreased with the increase of cutting speed.
Aiming at the shortcoming that the two-dimensional model cannot simulate the real cutting process, a more reliable three-dimensional finite element simulation model for milling Ti6Al4V was established in this paper. It is used to explore the influence of cutting parameters such as feed speed, tool speed and axial cutting depth on the milling force in the milling process. Therefore, a better selection of process parameters for high-speed milling of titanium alloy is obtained. Finally, based on this model, the morphology of the milling Ti6Al4V chip and the surface morphology of the workpiece after machining are explored.

2. Establishment of 3D Finite Element Model for Ti6Al4V Milling

2.1. Geometric model meshing and boundary condition setting
Cemented carbide YG8 is used as tool material and Ti6Al4V is used as workpiece material in this paper. In order to reduce the influence of geometric parameters of the milling cutter on the milling force, the cutter is defined as a rigid body. The tool radius is R6, the rake angle is 10°, and the relief angle is 0°. The size of the workpiece is 40mm×20mm×10mm.

Hexahedral C3D8R mesh element is used in the mesh division of the workpiece in order to make the calculation accuracy of the simulation model higher. The hexahedral element in the mesh has the characteristics of high calculation accuracy and good deformation performance. The tool adopts tetrahedral C3D4 mesh cell, and the mesh algorithm adopts default algorithm and non-standard internal cell growth. In order to simplify the model and reduce the amount of calculation, the whole workpiece is divided into two parts. The upper part is the main part of the simulation, using a dense grid, and the lower part is using a sparse grid.

In the process of 3D milling simulation, the cutter is defined as a rigid body to simplify the model. By setting the reference point, the tool moves with the reference point. The speed in the Z-axis direction and the rotation speed in the Y-axis direction are applied to the reference point. It is used to simulate the forward feed of the tool and its own rotational movement, so as to realize three-dimensional dynamic milling processing. At the same time, the 5 faces of the lower half of the workpiece are completely fixed. It is used to simulate the clamping requirements of the workpiece on the machine tool. The established 3D model is shown in Figure 1.

| Tool material performance | Physical quantities | YG8 |
|---------------------------|---------------------|-----|
| Density (g/cm³)           | 11.9                |
| Modulus of elasticity E/MPa | 534000             |
| Poisson's ratio v          | 0.22                |
| Coefficient of thermal conductivity λ/ (Wm⁻¹K⁻¹) | 50         |
| Coefficient of thermal expansion / (1/°C) | 4.7     |
| Impact toughness (J/cm²)  | 2.5                 |

| Workpiece material performance | Physical quantities | Ti6Al4V |
|--------------------------------|---------------------|---------|
| Density (g/cm³)                | 4.43                |
| Modulus of elasticity E/MPa    | 113000              |
| Poisson's ratio v              | 0.342               |
| Coefficient of thermal conductivity λ/ (Wm⁻¹K⁻¹) | 7        |
| Coefficient of thermal expansion / (1/°C) | 9.1 |
| Melting point /°C              | 1680                |
| Impact toughness (J/cm²)       |                     |

2.2. Selection of constitutive model for materials
The material properties of Ti6Al4V lead to high temperature, large strain and high strain rate during milling. Therefore, a constitutive model which can accurately describe the relationship between stress and strain, strain rate and temperature is needed under these conditions. Johnson-Cook material
constitutive model can more accurately describe the strain rate strengthening, strain hardening and heat softening effects of materials [8]. And its simple structure is suitable for metal cutting at high strain rate and high temperature. Its theoretical model is as follows:

$$\sigma = (A + B\varepsilon^n) \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\varepsilon_0} \right) \right] \left[ 1 - \left( \frac{\theta - \theta_r}{\theta_m - \theta_r} \right)^m \right]$$  \hspace{1cm} (1)

Type of $\sigma$ as the flow stress, $\varepsilon_0$, $\theta_r$ reference strain rate and reference temperature respectively, take $\varepsilon_0 = 0.001$ s$^{-1}$, $\theta_r = 20$ °C; $\theta_m$ is the melting point of the material; A, B, n, C and M are the material parameters, in which the strain strengthening term coefficient of the reaction material is A, B and n. The strain rate strengthening term coefficient is C, and the reaction heat softening coefficient is M.

In formula (1), $(A + B\varepsilon^n)$ is the strain strengthening effect of the material. $[1 + C \ln \left( \frac{\dot{\varepsilon}}{\varepsilon_0} \right) ]$ is the law between logarithmic strain rate and flow stress. $[1 - \left( \frac{\theta - \theta_r}{\theta_m - \theta_r} \right)^m ]$ describes the relationship between the temperature $\theta$ and the exponential exponential and the flow stress. Table 1 shows the Johnson-Cook material constitutive model parameters of Ti6Al4V.

| $A$/MPa | $B$/MPa | n  | C    | m    |
|---------|---------|-----|------|------|
| 1098    | 1092    | 0.93| 0.014| 1.1  |

Table 1: Johnson-Cook material model parameters.

2.3. Criteria for chip separation

The success of the simulation cannot be separated from an effective and appropriate material failure model. At present, a large number of studies have confirmed that the material failure of titanium alloy in the processing process follows the Johnson-Cook dynamic failure model [9]. The model comprehensively considers the effects of stress, strain rate, and temperature. When the material parameter $\omega$ is $\geq 1$, the mesh element fails. The workpiece begins to fracture and the material fails. Failure parameters are defined as follows:

$$\omega = \sum \frac{\Delta \varepsilon^{pl}}{\varepsilon_f^{pl}}$$  \hspace{1cm} (2)

Where $\Delta \varepsilon^{pl}$ is the equivalent plastic strain rate increment; $\varepsilon_f^{pl}$ is the set critical failure strain value, and $\varepsilon_f^{pl}$ can be expressed as:

$$\varepsilon_f^{pl} = \left[ d_1 + d_2 \exp \left( \frac{d_3 \varepsilon_0}{\dot{\varepsilon}_0} \right) \right] \left[ 1 + d_4 \ln \left( \frac{\dot{\varepsilon}}{\varepsilon_0} \right) \right] \left[ 1 - d_5 \left( \frac{\theta - \theta_r}{\theta_m - \theta_r} \right)^m \right]$$  \hspace{1cm} (3)

Where $\dot{\varepsilon}_0$ is the reference strain rate; $\varepsilon_0$ is the plastic strain rate; $d_1$-$d_5$ is the fracture parameter of the material at or below the transition temperature. Specific parameters of the Johnson-Cook shear failure model of Ti6Al4V are shown in Table 2.

| $d_1$ | $d_2$ | $d_3$ | $d_4$ | $d_5$ |
|-------|-------|-------|-------|-------|
| -0.09 | 0.25  | -0.5  | 0.014 | 3.87  |

Table 2: Johnson-Cook shear failure model parameters.

3. High Speed Milling Test Verification

In order to verify the accuracy of the 3D milling finite element model established in this paper. The vertical milling cutter of the same specification in the three-dimensional finite element simulation model is used. The machine tool uses YCM-V116B vertical machining center. The dynamometer uses YDX-III9702 to test the milling force. Milling parameters were $v_c=25$ m/min, $n=5000$ r/min, $a_v=2$ mm, $a_e=6$ mm.
Table 3  Comparison of experimental and simulation results.

| Project          | Direction of feed $F_x$ | The radial direction $F_y$ | The axial direction $F_z$ |
|------------------|-------------------------|---------------------------|--------------------------|
| Simulation value | 315                     | 145                       | 304                      |
| The test results | 282                     | 130                       | 265                      |
| Percentage error | 11.7%                   | 11.5%                     | 14.7%                    |

It can be seen from Table 3 that the maximum error between the simulated value and the experimental value is less than 15%. Considering that all the conditions in the simulation are in the optimal state. And the model can be used to simulate the milling force.

4. Orthogonal Test Parameter
Changes in feed rate, tool speed and axial depth of cut have a direct effect on the milling force. However, the impact of these three factors on the milling force is unclear. In order to explore the effect of these three on the milling force and the magnitude of the effect of these three. This article comprehensively considers the advantages and disadvantages of the single factor experiment method and the orthogonal experiment method. Finally chose the orthogonal test plan[10]. Combining with the content to be explored in this article, the experimental group of simulation analysis is designed by L9 (3^3) orthogonal table. The factors are feed rate, tool speed, and axial cutting depth. The evaluation standard is the magnitude of the milling force in the three directions of X, Y, and Z during the machining process. Table 4 shows the specific factors and levels.

Table 4  The level and factors of orthogonal experiment.

| Level | Feed speed (m/min) | Cutting tool rotation speed (r/min) | Axial cutting depth /mm |
|-------|--------------------|-------------------------------------|-------------------------|
| 1     | 25                 | 3000                                | 1                       |
| 2     | 30                 | 5000                                | 2                       |
| 3     | 35                 | 7000                                | 3                       |

5. Results and Discussion

5.1. Simulation process analysis
The different stages of the three-dimensional milling finite element simulation process are shown in Figure 2. According to the figure, the chip is separated in the form of fragmentation in the milling process of titanium alloy. As shown in Figure 2(a), the stress nebula of the cutter and the workpiece just in contact with each other. At this time, the cutter has not cut into the workpiece. And the workpiece is extruded by the blade, resulting in plastic deformation of the workpiece. At this time, the maximum stress value is about 1595MPa. As shown in Figure. 2(b), when the tool cuts into the workpiece, the material of the workpiece is damaged. And the plastic deformation is transformed into material failure. The stress value drops.

Figure 2  Stress nephogram of different stages of simulation process.
5.2. Analysis of orthogonal test results

Perform simulation tests on the model. And carry on the range analysis to the obtained simulation data. The results are shown in Table 5. The X direction is the tool feed direction, the Y direction is the tool radial depth of cut, and the Z direction is the tool axial depth of cut.

It can be seen from Table 5 that the influence of different cutting parameters on the milling force increases with the increase of the extreme value R. The order of influence of cutting parameters on the milling force is as follows: Axial cutting depth > Cutting tool rotation speed > Feed speed. The evaluation index selected in the test is the milling force, so the smaller the better. Therefore, the level corresponding to the minimum value of T1, T2 and T3 among the three factors should be selected. Where Ti represents the sum of milling forces at the i level of each factor. And R represents the range of Ti under each factor. According to the calculation results in Table 5:

Feed speed: T3 > T2 > T1; Cutting tool rotation speed: T1 > T2 > T3; Axial cutting depth: T3 > T2 > T1.

| Level | Feed speed | Cutting tool rotation speed | Axial cutting depth |
|-------|------------|----------------------------|--------------------|
| T1    | 474        | 1051                       | 334                |
| T2    | 673        | 535                        | 644                |
| T3    | 845        | 406                        | 1014               |
| R     | 371        | 645                        | 680                |

Primary and secondary order: Axial cutting depth > Cutting tool rotation speed > Feed speed
optimal level: 25
optimal combination: (25)~(7000)~(1)

Therefore, the optimal combination of cutting parameters can be obtained from the orthogonal analysis table as follows: 25m/min(Feed speed), 7000r/min(Cutting tool rotation speed), 1mm(Axial cutting depth).

Use the same method to analyze Fy and Fz. Then you can get the same conclusion as Fx. By comparing the range analysis tables of milling forces in three directions, it can be found that the influence of the change of cutting parameters on the milling forces in each direction is different. It has the greatest influence on the milling force in the x direction, followed by the y direction, and finally the z direction. The X direction is the main cutting direction, so the milling force in this direction is most significantly affected by the cutting parameters, which indirectly proves the accuracy of the model.

Figure 3(a) shows the influence trend of tool speed and axial cutting depth on the milling force, and the optimal matching parameters of the minimum milling force are obtained: n (6000~7000) r/min+up
(1~1.5) mm, that is "High speed + Low cutting depth". When the speed is higher and the cutting depth is smaller, the milling force is smaller, which is consistent with the actual processing.

Figure 3(b) shows the influence trend of tool speed and feed speed on milling force. According to the analysis of the figure, although there are differences in the optimal combination of different workpieces, the overall trend is basically the same. That is, to maintain low milling force in the milling process, "High speed + Low feed" should be selected. The tool speed and feed speed cooperate to complete the cutting of the workpiece. "Low speed + High feed" will lead to the cutting of each tooth of the tool on the workpiece greatly increased. The increased amount of workpiece removal will increase the friction between the chip and the tool. And too much cutting will produce greater plastic deformation. It will increase the energy consumed by cutting, so it will increase the milling force. "High speed + Low feed" will greatly reduce the cutting amount of each tooth, which reduces the friction between the chip and the tool and the plastic deformation of the chip, so the milling force significantly decreased.

5.3. Analysis of chip shape and workpiece surface quality

The chip morphology under the condition of "Low feed, High speed" is shown in Figure 4. Figure 4(a) is the plastic strain diagram of the chip when the tool just cut into the workpiece. At the beginning of cutting, the cutting temperature is low. The workpiece material is relatively "hard". The removal of material requires a higher state of stress. And the chips produce large plastic deformation. Figure 4(b) is the chip plastic strain diagram after the cutting process is stable. Due to the large amount of heat generated in the later cutting process. The material has heat softening effect. The workpiece becomes "soft" and is easier to be cut off. Therefore, the chip does not have large plastic strain, and the workpiece material is directly cut down by the tool.

The chip morphology under the condition of "high feed, low speed" is shown in Figure 4(c). At this time, due to the combined action of higher feed speed and lower rotational speed, the "intermittent cutting" characteristic of milling is gradually weakened. The milling process is changed to the "continuous cutting" of turning. The cutting time of each tooth of the tool in the workpiece is lengthened. The cutting amount of each tooth is greatly increased. Under the action of high temperature and high strain, the chip forms continuous sawtooth chip.
Figure 5 is the surface residual stress diagram of the machined workpiece. Figure 5(a) is the surface residual stress diagram of the workpiece under the condition of "High feed and Low speed". And Figure 5(b) is the surface residual stress diagram of the workpiece under the condition of "Low feed and High speed". It can be seen from the figure that "Low feed, High speed" can not only reduce the milling force in the cutting process, but also get a better surface topography. Under the condition of "High feed and Low speed", the surface morphology of the workpiece after machining has larger and more surface pits. This is because a larger amount of removal will result in greater plastic deformation of the workpiece. And the chip changes from a "shear cut" state to a "plastic tear" state. At this time, the cutting temperature rises sharply. The material of the workpiece becomes "soft", so that the excess material is "torn apart" under the action of the tensile stress between the inside of the material. Finally, more surface pits are formed.

According to the residual stress diagram of the workpiece surface in Figure 5, the machined surface under the condition of "High feed and Low speed" produces deeper but uneven work hardening. The uneven work hardening will lead to the unstable quality of the processed workpiece, which is not conducive to the actual production activities. Therefore, the processing state of "High feed, Low speed" should be avoided.

6. Conclusions
In this paper, 3D finite element model is established based on ABAQUS, and a more real cutting process is simulated. Follows, the research lays a foundation for the optimization of processing parameters of high speed milling Ti6Al4V.

(1) Based on the three-dimensional milling finite element model, the variation curve of the milling force was obtained. The influence law of the parameters on the milling force in all directions was revealed. The error between the milling force test results and the simulation results was within the allowable range, which confirmed the accuracy of the three-dimensional model.

(2) The influence of cutting parameters on the milling force from high to low is: Axial cutting depth > Cutting tool rotation speed > Feed speed.

(3) Milling process should be as far as possible to choose "Low feed, High speed" under the milling parameters.

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