Simulation analysis of titanium alloy micro-drilling based on thermo-mechanical coupling

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Abstract—With the increasing demand for high precision micro parts in machining field, the development of micro hole drilling technology, especially the finite element simulation technology is rapidly promoted. However, there are many limitations in the simulation of micro-drilling, such as element size, computational efficiency, chip forming, etc. In the present work, a finite element software, Abaqus has been used to simulate the thermal-mechanical coupling micro-drilling process of titanium alloy material, and the key technologies, such as twist bit modeling, material constitutive model, chip separation criterion and element division, were investigated. Through simulation, it was found that with the increase of rotational speed and the decrease of feed speed, chip shape gradually fragmented, in addition, thrust force and torque diminished. Since chip shape, thrust force and torque are important factors affecting drilling quality and tool life, the work could offer important guiding significance for cutting parameter optimization.

1. Introduction

With the development of production demand and industrial technology, the precision and miniaturization of products have become the development trend of manufacturing industry, with broad application prospects in electronic communication, aerospace, medical biology, automotive technology and military fields. Micro-hole mechanical drilling is one of the most basic micromachining techniques, due to its low cost, high precision and efficiency characteristics \[1\].

Since the 1950s, titanium alloy has gradually become an important structural metal material. Compared with traditional metal materials, titanium alloy has the characteristics of high strength, good corrosion resistance, high heat resistance and small density. But titanium alloy at the same time has the disadvantages of small deformation coefficient, cold hardening phenomenon, high cutting temperature, make it a typical difficult material. These defects lead to micro drilling easy to wear and break, processing surface quality, low processing efficiency process \[2\].

At present, lots of researches were primarily using simulation software such as Abaqus, Deform, and AdvantEdge to acquire thrust forces and temperatures \[3\]. Kumar \[4\] used Deform to investigate the effects of cutting speed and feed speed on torque, thrust and bit temperature. Yildiz \[5\] used Deform-3D to study the effect of tool coating and cutting parameters on thrust forces and torque, and also analyzed the effect of thrust forces and torque on the stresses of the drill bit. Priest \[6\] carried out a comparative analysis of chip separation methods using Abaqus and Deform-3D software and found that the updated-Lagrangian method with dynamic re-mesh was more accurate. Jomaa \[7\] used finite element analysis software Abaqus to establish two-dimensional finite element model to simulate the sawtooth
chip formation process of 7075 aluminum alloy during high-speed processing based on Lagrange numerical simulation method. Lv [8] studied the influence of cutting step length on grain refinement and hardening during chip formation through experiments and FEM chip forming simulation. However, most of the literatures focus on the two-dimensional cutting process, in contrast lack of in-depth research on the three-dimensional thermal-mechanical coupling drilling process and chip formation.

In this paper, the three-dimensional model and simulation model of micro drill bit are established through finite element method. The display dynamics module of finite element software Abaqus is applied to simulate the micro drilling process of titanium alloy material. Then the law of chip formation in drilling simulation and the influence of cutting parameters on drilling force and chip shape are analysed, which will provide reference for micro-drilling machining parameter optimization.

2. Establishment of the Finite Element Model

2.1. Geometry Model

(1) Due to the complex structure of the micro-drill, the 3D modeling software NX 12.0 was adopted. Referring to the manufacturing process and angle parameters of the drill, the rake and flank face were modelled to obtain the 3D model of the micro-drill. The modeling process is shown in Figure 1. To reduce the number of elements and shorten the calculation time, the 1.2 mm part of the front end of the bit was cut off, saved in step format and imported into Abaqus, as shown in Figure 2 (1).

(2) The geometry of the workpiece is relatively simple, established through the modeling function of Abaqus. As the micro-drill is 1 mm in diameter, the workpiece was set to a cylinder with 1.2 mm in diameter and 0.8mm in height, as shown in Figure 2 (2).

(3) In the Assembly module of Abaqus, the drill bit and workpiece were assembled to determine the mutual position relationship, so that the drill bit could complete the drilling simulation process at the specified position. The assembly diagram is shown in Figure 2 (3).

2.2. Material Parameters of The Model

Material constitutive model is a theoretical model used to describe the relationship between flow stress, strain, strain rate and temperature in materials. Because drilling is a strong nonlinear material removal process, large elastic-plastic deformation under high stress, high temperature and high strain rate of workpiece occur. Johnson-cook constitutive model is the most widely used in the cutting process. This model comprehensively considers the effects of processing hardening effect, strain rate effect and temperature softening effect on the dynamic mechanical properties of materials. Its mathematical expressions are as follows [9]:

\[ \sigma = \sigma_0 + \int_{0}^{\varepsilon} \left[ A + B \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \varepsilon \, d\varepsilon \]

\[ \dot{\varepsilon} = \frac{\sigma}{E} \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \left[ 1 - \left( \frac{\sigma}{\sigma_f} \right)^{\frac{m}{n}} \right] \]

\[ \dot{\varepsilon}_0 = \frac{A_0}{E} \left( \frac{T}{T_0} \right)^{\frac{n}{m}} \]

\[ \sigma_f = \frac{K}{\left( 1 - \frac{\Delta T}{T} \right)^{\frac{m}{n}}} \]

\[ \Delta T = T - T_0 \]

These equations are used to simulate the behavior of materials under dynamic loading conditions.
\[ \sigma = (A + B \varepsilon^n) \left(1 + C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \left(1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right) \]  

where \( \sigma \) is the equivalent stress, \( \varepsilon \) is the equivalent plastic strain, \( \varepsilon \) is the strain rate, \( \dot{\varepsilon}_0 \) is the reference strain rate, \( A \) is the initial yield stress, \( B \) is the hardening modulus, \( C \) is the strain rate coefficient, \( n \) is the strain hardening coefficient, \( m \) is the thermal softening coefficient, \( T \) is the process temperature, \( T_r \) is the room temperature, and \( T_m \) is the melting temperature of the workpiece. The constitutive model parameters of the TC4 material are shown in Table 1 [10], and other material parameters of the workpiece are shown in Table 2 [11]:

| A (MPa) | B (MPa) | C   | n   | m   | \( T_m \) (°C) | \( T_r \) (°C) | \( \dot{\varepsilon}_0 \) (s\(^{-1}\)) |
|---------|---------|-----|-----|-----|---------------|---------------|----------------|
| 880     | 331     | 0.012 | 0.8 | 0.34 | 1560          | 20            | 1              |

Table.1 The J-C constitutive model parameters for the TC4 material [10]

Table.2 Other material parameters for the TC4 material [11]

| Density (kg/m\(^3\)) | Young modulus (GPa) | Poisson’s ratio | Conductivity (W/(m·°C)) | Expansion (10\(^{-6}\)°C) | Specific heat (J/(kg·°C)) |
|------------------------|----------------------|----------------|-------------------------|-----------------------------|---------------------------|
| 4430                   | 109                  | 0.34           | 6.8                     | 10                          | 611                       |

2.3. Material Failure Criteria

During the cutting process, the workpiece cutting layer material experiences elastic deformation, plastic deformation, damage and fracture under the cutting edge. In order to accurately describe the chip separation process caused by material failure in the cutting process, it is necessary to choose a suitable chip separation criterion. Johnson-cook shear failure criterion is commonly used in cutting simulation, which belongs to the equivalent plastic strain criterion. In the cutting simulation, the equivalent plastic strain \( \Delta \varepsilon_{pl} \) on the workpiece element is calculated. When the element reaches the strain value \( \varepsilon_{pl} \) of failure separation, thus, the failure parameter \( \omega \) is equal to 1, the workpiece material fails to separate and chip is formed. The mathematical expression of failure parameter \( \omega \) is shown in Eq. (2) [12]:

\[ \omega = \sum \frac{\Delta \varepsilon_{pl}}{\varepsilon_{pl}} \]  

Where, \( \omega \) is the failure parameter, \( \Delta \varepsilon_{pl} \) is the equivalent plastic strain increment, \( \varepsilon_{pl} \) is the critical equal effect change, the expression is shown in Eq. (3) [12].

\[ \varepsilon_{pl} = \left[ d_1 + d_2 \exp \left( d_3 \frac{T_m}{q} \right) \right] \left[ 1 + d_4 \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 + d_5 \left( \frac{T - T_r}{T_m - T_r} \right) \right] \]  

Among them, \( p \) is hydrostatic stress, \( \alpha \) is mises stress, \( \dot{\varepsilon} \) and \( \dot{\varepsilon}_0 \) are material strain rate and reference strain rate respectively, \( T \) is material cutting temperature, \( T_m \) is material melting point and \( T_r \) is room temperature, \( d_1 \sim d_5 \) are material failure coefficients. The failure coefficient of TC4 is as shown in Table 3 [13].

Table.3 Failure coefficient of TC4 [13]

| \( d_1 \) | \( d_2 \) | \( d_3 \) | \( d_4 \) | \( d_5 \) |
|----------|----------|----------|----------|----------|
| -0.09    | 0.25     | -0.5     | 0.014    | 3.87     |

2.4. Part Mesh Division

The primary criterion of element division is avoiding element distortion to ensure the convergence and accuracy of simulation calculation. Secondly, the number of elements is the significant important factor affecting the simulation calculation time. Therefore, it is necessary to divide the part mesh reasonably to ensure the efficiency and accuracy of simulation calculation within the acceptable range.

Due to the complex tool structure, the tetrahedral mesh was used to divide it, whose type was the four-node thermally coupled tetrahedral unit (C3D4T). The global size of the element is 0.04mm. In order to improve the simulation accuracy, the mesh contacting with the main cutting edge and chisel
edge were partially refined, divided into 0.04mm. The generated tool element model is shown in Figure 3 (1).

In order to improve the calculation accuracy of the workpiece in thermo-mechanical coupling drilling simulation, the element type was set as eight-node thermo coupled hexahedron element (C3D8RT). The decrease of element size is beneficial to the calculation accuracy of chip forming and thrust force parameters, but the number of elements will increase exponentially. When the workpiece is given a global size of 0.02mm, the number of elements is 138480, meanwhile when the global element is set to 0.01mm, the number of elements is 1097600. The simulation calculation time increases by more than ten to twenty times. Similarly, the increase in the size of the workpiece will greatly increase the cost of computing time. Therefore, reasonable mesh size and workpiece size (the specific size is in module 2.1) were set based on the comprehensive consideration of the drill bit diameter and mesh size. The global mesh size was set as 0.02mm, and the mesh size in the feed direction of drilling should be less than the feed amount per tooth. Otherwise, the mesh will fail due to excessive deformation, resulting in simulation error or failure of chip generation, affecting the simulation accuracy. The minimum feed amount per tooth is 0.025mm/r, so the mesh size in the feed direction was set as 0.015mm. The length of the four sides of the element in contact with the workpiece and the main cutting edge was set as approximate value, which was conducive to chip generation. Therefore, the radial element size was refined to 0.015mm, and the final total mesh number of the workpiece was 224879. The workpiece element model is shown in Figure 3 (2).

![Tool mesh distribution and Workpiece mesh distribution](image)

**Fig.3 Cutting tool and workpiece element model**

**3. Results and Discussion of Simulation**

**3.1. Chip Formation**

The stress cloud map of the micro-drilling simulation process is shown in Figure 3. In the process of micro-drilling, the chisel edge part first contacts with the workpiece material for extrusion and friction, lead to elastic deformation. When the contact stress exceeds the yield limit of the material, the surface material is plastic deformed and the lattice dislocation occurs. Due to the limitation of the underlying material, slippage and distortion occur in the direction of the micro-bit rotation, as shown in Figure 4 (1). As the shear stress of the surface material exceeds the fracture strength of the material, microcracks will occur. With the drilling process, the microcracks gradually expand, and the cutting layer material is squeezed and cracked by the chisel edge, and eventually forms chips, as shown in Figure 4 (2). With the drilling, the main cutting edge gradually participates in the cutting. Due to the different flow speed in the direction of thickness and the direction of main cutting edge, the chips curl upward and sideways, and the initial chips appear conical, as shown in Figure 4 (3). With the increase of drilling depth, the initially generated chips are constantly pushed by the newly generated chips, flowing in the discharge groove, and the curl degree gradually intensifies, causing the formation of spiral chips. After the main cutting fully participates in the cutting, the width of the chips will not increase, as shown in Figure 4 (4).
Figure 5 shows the temperature cloud diagram of the chip morphology changing with the cutting parameters at a drilling depth of 0.45 mm. As can be seen from Figure 5, the highest temperature during the drilling process is in the contact between the cutting edge and the chip. This is because the cutting layer becomes chips after shear slip on the front tool surface. The chip here and the tool front surface friction is the most serious, so the temperature is also the highest. At the same time, we can see from the figure that, with the increasing rotation speed and the decreasing feed speed, the fragmentation feature of the chip state becomes more and more obvious. When the spindle speed is kept constant (3000 rpm), the chip pattern changes with the feed speed. When the feed speed is high (15 mm/s), the main form of chips is spiral chip. The discharge process of cutting debris is relatively smooth; As the feed speed decreases (10 mm/s), the chip morphology is mainly continuous chip. This is due to the friction between the micro-hole chip discharge groove and the hole wall, resulting in the chip rotation is difficult to maintain. Chip discharge groove is easy to plug, is not conducive to chip discharge; When the feed speed is low (5 mm/s), the chips are difficult to form, fragmented or without debris. This is because the ploughing cutting plays a major role in the cutting process, and the size effect occurs. With the refinement of the workpiece mesh and comparison with the actual micro-drilling experiment, the size effect and the minimum chip thickness can be studied. When the feed velocity remains constant (15 mm/s), as the spindle speed increases (3000 rpm, 4000 rpm, 6000 rpm), the chip shape gradually changes from spiral, ribbon shape to chip shape or no chip formation.

Fig.4 Cutting chip formation process in micro-drilling processing

Fig.5 Shape change of microdrill chips
3.2. Thrust Force and Torque
Cutting force is an important factor affecting the life of micro-drill. As shown in Figure 6, the thrust force and torque change curves at the same cutting parameter (6000 rpm, 15 mm/s).

As can be seen from the change curve of drilling force in the figure, the thrust force of drilling increases gradually as the chisel edge and the main cutting edge gradually contact with the workpiece after the beginning of drilling. When the cutting time reaches 0.02 s, the main cutting edge fully participates in the cutting, and the thrust force reaches the maximum and fluctuates at a stable level. Similarly, the change law of torque is similar to the change law of cutting force. As the chisel edge and the main cutting edge gradually contact with the workpiece, torque increases gradually and fluctuates at a steady level after steady cutting. In the finite element simulation, continuous workpiece is separated into element elements, and the material removal of workpiece is realized through the separation of element elements and workpiece. When the mesh element is separated from the workpiece, the abrupt change of thrust force will be caused, so the curves of thrust force and torque have obvious fluctuation.

The thrust force and torque value under different cutting parameters are obtained, as shown in Figure 7 (1) and (2) respectively. When the feed speed remains unchanged, the spindle thrust force and torque decrease with the increase of the spindle speed. The main reason is that with the increase of speed, the number of times of cutting per unit time increases. While the thickness of cutting per unit time is unchanged, so the amount of single cutting is reduced, and the thrust force and torque of the tool are reduced. When the spindle speed remains unchanged, the spindle thrust force and torque increase with the feed speed. The reason is that as drilling depth per unit time increases, microdrill bit feed per turn increases. The increase in the thickness of a single cut increases the resistance of the bit to the material, thus increasing the thrust force and torque on the bit.

4. Conclusion
In this paper, the nonlinear finite element software Abaqus was used to conduct thermal-mechanical coupling simulation on the micro-hole drilling process of TC4 material, and the main conclusions are as follows:
(1) In the finite element simulation of micro drilling, when the element size is controlled within one sixth of the feed of each tooth, and the damage displacement is controlled as 0.6 to 0.8 times the size of the element, the element does not distort easily during the cutting process, and the generated chip quality
is fine. At the same time, reasonable local refinement, avoiding global mesh refinement, generates almost the same results, while improving the efficiency of 2-3 times.

(2) The formation process of cutting chip includes four stages: chisel edge extrusion material, chisel edge chip generation, part of main cutting edge cutting and the whole main cutting edge cutting. As the feed velocity decreases and the spindle speed increases, the chip shape of the material gradually changes from spiral, ribbon to debris and little debris.

(3) With the increase of the feed speed and the decrease of the spindle speed, the thrust force and torque of the workpiece gradually increase in the micro-drilling simulation of the material.

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