Simulation and Research of Aerospace Material Milling Based On ABAQUS

Yanzhong Zhang\textsuperscript{1*}, Xiaohua Huang\textsuperscript{1}

\textsuperscript{1}School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, Jiangsu, 210094, China
\textsuperscript{*}Corresponding author’s e-mail: 609856977@qq.com

Abstract. In this paper, ABAQUS simulation software is used to establish the model of the tool and the blank. Through the simulation of the single tooth milling process of 2024 aviation aluminum alloy material, the temperature and stress distribution cloud diagram, the cutting force curve are obtained. The effects of various cutting factors on the milling temperature are studied using simulation methods. The study found that the milling temperature increased with the increase of the axial depth of cut, radial depth of cut, cutting speed, and feed per tooth, among which the cutting speed had the greatest effect on temperature.

1. Introduction

Aluminum alloy materials are widely used in parts of high-precision instruments such as aerospace, because they have the advantages of high specific strength and light weight. When processing aluminum alloy materials, due to the influence of heat and force generated during cutting, the processed parts are easily deformed, so the study of the cutting mechanism of aluminum alloy materials is particularly important [1-2].

The traditional research method is to pass a large number of cutting experiments, which takes more time and money [3]. With the continuous advancement of computer technology, more and more researchers have begun to use simulation methods to study the cutting mechanism of metal materials. This method is more convenient and faster, and can visualize the results [4-5]. At present, there are two main cutting simulation methods: two-dimensional cutting simulation and three-dimensional cutting simulation. Among them, the two-dimensional cutting simulation results are more convenient to observe and the operation is simpler, but there are fewer factors that can be studied. In comparison, three-dimensional cutting simulation is more practical for cutting processing, more influential factors are considered for cutting, and the results obtained by simulation are more correct and referable.

In this paper, ABAQUS software was used to establish a 3d milling model of 2024 aluminum alloy, including the shape parameters of the tool and the setting of material parameters. The milling process is simulated and studied.

2. Key technologies of finite element models Vibration signal acquisition experiment

2.1. Selection of constitutive model

In actual milling, the state change of the material is extremely complicated. The selected model needs to consider the relationship between multiple factors at the same time [6-7]. The Johnson-Cook model is selected in the form:
The expression consists of three parts, which represent the hardening of the material affected by the normal properties, strain rate and temperature. Among them A, B, n, c, m are values related to the material, which can be measured through tests.

2.2. Chip separation criteria

There are multiple failure modes to choose from in the software. The factors considered in the Johnson-Cook damage mode are more in line with the actual situation [8]. When $\omega > 1$, the material will fail and disappear, and the material will be separated to form chips. The definition is as follows:

$$\omega = \frac{\bar{\varepsilon}^0 + \sum \Delta \bar{\varepsilon}^m}{\bar{\varepsilon}^m}$$  \hspace{1cm} (2)$$

In the formula: $\bar{\varepsilon}^0$: Initial strain amount to be set; $\Delta \bar{\varepsilon}^m$: Strain increase amount; $\bar{\varepsilon}^m$: Set the maximum strain.

The calculation process is the superposition of the amount of strain increase in each analysis step. When the numerator is greater than the denominator, the material will fail, $\bar{\varepsilon}^m$ can be expressed as:

$$\bar{\varepsilon}^m = \left[ d_i + d_s \exp \left( \frac{d_i}{d_q} \right) \right] \left[ 1 + d_i \ln \left( \frac{\bar{\varepsilon}^0}{\hat{\varepsilon}_0} \right) \left( 1 + d_s \hat{\theta} \right) \right]$$  \hspace{1cm} (3)$$

In the formula: $d_i$-$d_s$: Material parameter; $\hat{\varepsilon}_0$: Strain rate setting value.

2.3. Contact friction model

In actual cutting, in addition to the shearing effect of the tool on the material, there is also friction between the cutting tool and the chip. Therefore, the setting of the contact friction in the simulation has a great impact on the chip shape, milling force simulation, and milling temperature prediction. There are mainly two types of friction between cuttings: adhesiveness and sliding, adhesive friction tends to occur around the tip of the knife, because the heat generated in this part of the area is not easy to release, affecting the state of the material and making it adhesive. After the heat is transferred to the outside, the temperature of the material will decrease and become stiff, so sliding friction will occur in the area far from the tip of the knife [9-10]. Coulomb’s law of friction is used to represent them as:

$$\begin{cases} \tau = \tau_c, \tau_c \leq \mu \sigma_n \\ \tau = \mu \sigma_n, \tau_c > \mu \sigma_n \end{cases}$$  \hspace{1cm} (4)$$

Where: $\tau$ is the friction stress; $\tau_c$ is the maximum shear stress; $\mu$ is the friction factor. operation.

3. Establishment of finite element model

First, according to the physical diagram of the tool, a model of the tool and cutting blank is established. According to the actual situation, the tool and blank are simplified, and only the cutting area is modeled. Figure 1 is the simplified model of the tool and blank.
The billet model was given 2024 aluminum alloy material parameters with damage parameters, and the tool model was given YG8 carbide material parameters without damage parameters. Table 1 shows the physical properties of the billet, and table 2 shows the physical and thermodynamic parameters of the tool.

### Table 1. Physical Properties of Billet.

| Property               | Value   |
|------------------------|---------|
| Density (g/cm³)        | 2.8     |
| Modulus of elasticity (Gpa) | 71       |
| Poisson's ratio        | 0.33    |
| Tensile strength (Mpa) | 440     |
| Yield strength (Mpa)   | 352     |

### Table 2. Physical and Thermodynamic Properties of the Tool.

| Property               | Value   |
|------------------------|---------|
| Density (g/cm³)        | 14.5    |
| Modulus of elasticity (Gpa) | 640  |
| Poisson's ratio        | 0.22    |
| Linear expansion Rate (m/m°C) | 4.5E-06 |
| Specific heat J/(Kg°C) | 220     |

The tool and blank models are transferred into the assembly module respectively. According to the cutting parameter combination selected in the simulation, the tool tip is moved down and to the left by 0.65mm and 0.1mm from the vertex position of the blank, to avoid the contact between the tool and the blank. Rotate a slight angle away from the blank.

The research contents of this simulation include: blank stress and temperature cloud diagram, three-way cutting force curve, tool temperature cloud diagram, and set the output result accordingly.

The initial temperature is set to 20 degrees, the bottom and sides of the blank are set to be fixed, the tool movement parameters are based on the selected cutting parameters, the cutting speed is 75.36m/min, and the feed rate per tooth is 0.09mm/z, including rotation and going in x-direction, the milling method of dry down milling.

Dividing the grid of the tool and the blank separately, in order to make the simulation result more accurate and reduce the calculation amount of the software, according to the simulation situation, the meshing of the cutting area of the tool and the blank involved in the simulation process is finer, the part of the grid that is not involved is relatively loose. Figure 2 shows the grid division of each part.

4. Finite element simulation results and analysis

4.1. Stress field analysis

Figure 3 shows the cloud diagram of the stress field distribution during milling. Observation shows that with the cutting of the teeth, the stress field distribution in the chip changes continuously. The maximum value of the stress is distributed during the initial separation and bending of the material to form the chip position, that is the first deformation zone, because the material in this position has the largest amount of instantaneous deformation. With the continuous rotation of the tool, the stress field distribution area is constantly expanding, but the maximum value is still mainly distributed in the first deformation area. After the chip is detached from the substrate, the internal stress of the chip will not be reduced to zero immediately, but the remaining time will be gradually reduced to zero, which is the residual stress of the chip.
4.2. Temperature field analysis
Figure 4 shows the cloud diagram of the temperature field distribution during milling. It can be seen from the figures that the maximum temperature appears in the second deformation zone. This is because there is a lot of heat in the chip during cutting. The temperature will continue to rise under the friction of the front cutting surface, the maximum temperature is 290 degrees, then with the knife teeth cut out, the heat in the chip dissipates faster than the producing speed, and the maximum temperature drops.

4.3. Cutting force analysis
Figure 5 is a graph showing the change of the milling force in each direction during the simulation process. In the figure, Fx is the feed force, Fy is the radial force, and Fz is the axial force. As can be seen from the figure, the milling force curve continues to increase at the beginning of milling; when the tool and chip are completely in contact with each other and enters a stable state, the cutting force...
begins to stabilize, with slight fluctuations, this is because cutting with the transfer of heat and force, the presence of heat, the material will become soft and easy to cut, the cutting force required is small. The reduced heat generated by the reduction of the force will make the material hard and the cutting force will increase, so the cycle will continue. When the tool continuously cuts out the material, the cutting force will also start to decrease until it decreases to zero.

5. Analysis of the influence of milling parameters on milling temperature

The simulation method is used to study the change of the maximum milling temperature by changing the cutting parameters. Table 3 shows the milling parameters used in the simulation.

| v (m/min) | fz (mm/z) | ap (mm) | ae (mm) |
|-----------|-----------|---------|---------|
| 56.52     | 0.03      | 0.65    | 0.1     |
| 75.36     | 0.05      | 0.95    | 0.2     |
| 94.2      | 0.07      | 1.25    | 0.3     |
| 113.04    | 0.09      | 1.55    | 0.4     |

(a) Effect of cutting speed on milling temperature (b) Effect of feed per tooth on milling temperature

Figure 6. Influence of different milling parameters on milling temperature.

Figure 6 is a line chart of the maximum milling temperature when the milling parameters are changed. From Figure 6 (a), it can be seen that when milling 2024 aluminum alloy materials, the milling speed v increases and the polyline continues to increase. When it is large, the upward trend of the curve slows down. As shown in Figure 6 (b), with the increase of the feed per tooth fz, the temperature curve continues to rise. When fz increases in the range of 0.03mm/z-0.09mm/z, the temperature increases by 14 degrees, and the phase In comparison, the effect of feed per tooth on the milling temperature is smaller than the milling speed. This is because the increase in feed per tooth will increase the chip volume, but the deformation coefficient of the chip will decrease, which will reduce the work consumed by the material removal volume of the same volume. At the same time, the heat transfer between the chip and the tool increases, so that more heat is discharged with the chip. As can be seen from Fig. 6 (c), the fold line keeps rising with the increase of the axial depth of cut ap, but
from the perspective of the amount of change, the effect of axial depth of cut on the milling temperature is small. It can be seen from Fig. 6 (d) that the radial cutting depth $a_e$ increases from 0.1mm to 0.4mm, and the change of the temperature curve is small. Generally speaking, radial cutting depth has little effect on the milling temperature. From the above comparative analysis, it is known that the cutting speed has the greatest effect on temperature during cutting.

6. Conclusion
In this paper, the method of simulation is used to establish the model of the tool and the blank, and the milling process of the 2024 aluminum alloy material is simulated.

From the results obtained by simulation, it can be known that the maximum value of material stress during milling occurs in the first deformation zone of the material separation and deformation to form chips, and the maximum value of the milling temperature occurs in the second deformation zone. Residual stresses still exist in the chip after it is separated from the matrix.

Based on this method, the effects of cutting speed $v$, feed per tooth $f_z$, axial cutting depth $a_p$ and radial cutting depth $a_e$ on milling temperature were simulated and studied. The research finds that milling temperature increases with the increase of $v$, $f_z$, $a_p$ and $a_e$, but they have different effects on milling temperature, and the biggest impact on the milling temperature is $v$. The research results can be used as a reference for the study of material cutting mechanism and the reasonable selection of cutting parameters in actual cutting processing.

References
[1] Ge M J 2016 Modeling and Simulation of 7050-T7451 3D Micro Milling for Aluminum Alloy J. Tool Technology. 50 59-62
[2] Cheng Q L 2006 Finite Element Simulation of High Speed Milling of Aviation Aluminum Alloy J. Journal of Zhejiang University (Engineering Science). 01 113-117
[3] Xia L L 2013 Simulation and experimental research on milling force of aluminum alloy based on DEFORM-3D J. Mechanical Design & Manufacturing. 04 85-87
[4] Xu W G 2019 Research on machining method of aviation aluminum alloy parts with large cutting capacity J. Nonferrous metal processing. 48 30-32
[5] Peng C X 2018 Research on the Influence of JC Constitutive Model on the Simulation of 2D Cutting of 7050 Aluminum Alloy J. Tool Technology. 52 59-62
[6] Zhang W 2013 Constitutive relationship and failure model of 2A12 aluminum alloy J. Acta Armamentari. 34 276-282
[7] Sun H L 2017 Two-dimensional simulation of aviation 7075 aluminum alloy cutting based on ABAQUS J. Journal of Tianjin University of Technology.36 83-88
[8] Jia C L 2018 Finite element simulation of Johnson-Cook constitutive model of 7A52 aluminum alloy J. Ordnance Material Science and Engineering. 41 30-33
[9] Li D B 2004 Research and application of high-speed milling processing technology of J. Tool Technology. 4 14-16
[10] Sutter G 2013 Very high speed cutting of Ti–6Al–4V titanium alloy – change in morphology and mechanism of chip formation J. International Journal of Machine Tools and Manufacture. 50
[11] Qu H J 2013 Finite element analysis of strain in right-angle cutting process J. Mechanical science and technology. 32 59-62