Cutting Characteristics of Flexible Joint Key Structure Based on Finite Element Method

Jiajing Guo¹, Xin Jin¹, Ruilin Gao¹, Zhongpeng Zheng² and Chaojiang Li*¹

¹School of Mechanical Engineering, Beijing Institute of Technology, Beijing, 100081, China
²Department of Mechanical Engineering, Tsinghua University, Beijing ,100084, China
*Corresponding author Chaojiang Li: mecjli@bit.edu.cn

Abstract. According to the characteristics of small thickness, low rigidity and easy deformation for the thin-walled structure of flexible joint, the geometric and material constitutive models of flexible joint Thin-walled structure based on the ABAQUS software were established. And the numerical simulation and data analysis were carried out through the orthogonal experiment method. The influence of different cutting parameters on the cutting characteristics of Thin-walled structures was discussed. The prediction model of deformation is consistent with the cutting parameters of the Thin-walled structure. Experiments results show that the most considerable deformation of the Thin-walled structure was not the thinnest point of the Thin-walled structure, but the place where close to the Thin-walled structure in the thin-wall processing direction. This model provides the foundation for cutting process simulation and process optimization.

1. Introduction
Flexible joints are the critical components of gyroscopes in aeronautical instruments. However, the structure of its essential parts is complex, and the requirements for position accuracy, dimensional accuracy, surface quality and mechanical properties of material processing are more demanding[1]. The four thin walls of the flexible joint are the essential structure to show the "flexibility" of the flexible joint, which is usually formed by milling and boring four pairs of blind holes[2]. If the thickness and deformation of the four thin-walled positions differ, the inconsistency will directly affect the performance of the dynamically-tuned resonant gyro. In the fine boring process, different cutting parameters produce different cutting forces, affecting the deformation of the thin wall. Therefore, carrying out a simulation of the cutting process of flexible joints and accurately predicting the influence of different cutting parameters on thin-wall deformation is of great significance for optimizing the processing parameters of the fine boring process, improving the performance of the dynamic resonant gyroscope, and reducing the experiment cost.

At Present, many scholars have studied the cutting characteristics of Thin-walled structures. Yang Yang [12] and others studied the influence of cutting parameters on the deformation of TC4 alloy Thin-walled structure. Zhang Chaoxiao [2] optimized the processing parameters of flexible joints, and Zhou Chunlei [3] studied the influence of the constitutive model parameters on the cutting process simulation. Yaich [13] et al. proposed the influence of JC constitutive parameters on Ti6Al4V cutting simulation results. However, few simulation studies delineated the cutting characteristics of thin-walled flexible joints.
Based on the ABAQUS software, considering the different JC constitutive parameters obtained by different experimental methods for flexible joint materials, the simulation model for the fine boring process of flexible joints is established in this paper. The orthogonal experiment method was used to carry out numerical simulation calculations, explore the influence of JC constitutive parameters and cutting parameters on Ti6Al4V thin-wall cutting force and thin-wall deformation, and fit the prediction model of thin-wall deformation and cutting parameters.

2. Finite element model for thin-wall cutting

2.1. Thin-wall cutting geometry model and mesh division
The thin-wall shape and processing method of the four directions of the flexible joint are identical. One of the thin walls can be simplified as a flat two-dimensional Figure for research. The three-dimensional model of the flexible joint is depicted in Figure 1(a). The thin wall is after milling, the workpiece is fixed in the chuck, and the cemented carbide boring cutter is used for boring processing. The cutting method is illustrated in Figure 1(b).

![Figure 1. (a) Thin-wall cutting simulation model   (b) Meshing diagram   (c) Thin-wall cutting simulation model   (d) Mesh division](image)

A two-dimensional cutting model is established based on the ABAQUS/Explicit. The fine boring process in actual machining is simulated for the thin-walled part of the flexible joint. The cutting model consists of two parts: the workpiece and the tool. The workpiece is formed on an initial square workpiece of 3.40mm×2.76mm with a radius of 1.49mm arc cut off on both sides, and the thickness of the thin wall is 50μm. The tool is cutting clockwise along an arc, with a rake angle of 10°, a relief angle of 30°, and the radius of the tool tip point arc is 1μm. The thin-wall cutting simulation model is depicted in Figure 1(c).

The grid is divided, as illustrated in Figure 1(d). The area closer to the cutting layer adopts a dense grid. A total of 16 layers of dense grids with a size of 1um×1um×1um are distributed throughout the cutting layer. The area far from the cutting layer is set as a sparse grid to balance the calculation speed and accuracy. In the boring process in Figure 1(b), the workpiece is fixed by the chuck, the boring bar initiates the feed motion, and the tool rotation is the main motion. Therefore, the boundary conditions constrain the upper and lower bottom surfaces of the workpiece. The tool can only rotate clockwise...
along the Z-axis. It constrains the five degrees of freedom along the X-axis, Y-axis, and Z-axis and rotation around the X-axis and Y-axis. The rake face is defined as the main contact surface, and the workpiece is defined as the slave contact surface.

2.2. Thin-wall cutting material model

In the process of thin-wall processing, the processed material will undergo elastoplastic deformation, which is a process of thermodynamic and dynamic coupling. Establishing an accurate thin-wall cutting material model should reflect the elastoplastic deformation of the material. This plays a key role in the accuracy of the calculation results of thin-wall cutting characteristics. Moreover, phenomena such as strain hardening and strain strengthening will occur in Ti6Al4V boring. Therefore, the Johnson-Cook constitutive model should be used for simulation calculations, which can showcase the mechanical changes of metals under high strain, strain rate and temperature [2]. The calculation expression is as follows:

$$\sigma = (A + BE_p^n) \left(1 + C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_p}\right) \left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right]$$

In the formula, \(\sigma\) denotes the equivalent stress; \(A\) is the yield strength; \(B\) is the hardening modulus; \(C\) is the strain rate sensitivity coefficient; \(m\) represents the thermal softening coefficient; \(n\) is the strain rate dependency coefficient; \(\dot{\varepsilon}\) is the equivalent plastic strain; \(\dot{\varepsilon}_p\) is the equivalent plastic strain; \(T\) is the current temperature; \(T_m\) is the melting point of the material; \(T_r\) is the room temperature.

| Source              | \(A\)/Mpa | \(B\)/Mpa | \(n\) | \(C\)   | \(m\)  |
|---------------------|------------|------------|-------|---------|--------|
| Johnson [6]         | 862.5      | 331.2      | 0.34  | 0.012   | 0.8    |
| Leseur et al. [4]   | 1098       | 1092       | 0.93  | 0.014   | 1.1    |
| Li et al. [5]       | 968        | 380        | 0.421 | 0.0197  | 0.577  |
| Özel et al. [7]     | 803.85     | 544.57     | 0.3616| 0.05    | 1.041  |

In the thin-wall cutting simulation model, the JC constitutive parameters of Ti6Al4V under different experimental conditions are shown in Table 1. Its physical and mechanical properties adopt the parameters proposed by Ye [9] and Zang [10]. The physical parameters of using were proposed by Xu [11] et al.

3. Numerical simulation results and analysis

3.1. Orthogonal test of cutting parameters

Under the premise of using the constitutive parameters obtained by Johnson et al., taking the cutting amount as the influencing factor, and extracting the maximum value \(d\) of the thin-wall deformation as a result, the displacement vs. time diagram is yielded, as shown in Figure 2(a). The cutting speed \(V_c\) in the cutting parameters is selected as 1000 r/min, 3000 r/min, and 5000 r/min. The feed amount \(f\) per revolution is 2.5μm, 5μm, 7.5μm. The cutting depth \(a_p\) is 10μm, 5μm, 2μm. Using the extraction method in Figure 2(a), a three-factor three-level orthogonal model L9 (34) was established, as listed in Table 2, where \(d\) denotes the maximum thin-wall deformation and \(K_i\) is the sum of horizontal deformations under different factors. \(R\) is range.
Figure 2. (a) Result value point  (b) Deformation cloud image

The data in Table 2 shows that the deformation of the thin wall in Experiment is the most negligible. It can be concluded from the comparison of the R value that under the same constitutive parameters and tool conditions, the main factors affecting the deformation of the thin wall are cutting depth, feed rate and cutting speed.

To better express the relationship between the thin-wall deformation \(d\) and the cutting speed \(V_c\), the feed amount \(f\), and the cutting depth \(a_p\), the method of linear fitting regression equation can be used. Now assuming that there is a linear equation:

\[
d = b_0 + b_1 V_c + b_2 f + b_3 a_p
\]  

(2)

The experimental data is input into Matlab through the linear fitting regression equation, get \(b_0 = 0.9965, b_1 = -0.0002, b_2 = -0.1316, b_3 = 1.0266\), the square of the residual is 0.8965, the regression model is relatively accurate. The thin-walled deformation variable \(d\) is a non-negative value, and the absolute value is used to express it. Equation (2) can be expressed as:

\[
d = | -0.0002V_c - 0.1316f + 1.0266a_p + 0.9965 |
\]  

(3)

To verify the accuracy of formula (3), the cutting parameters used in actual machining are used to carry out simulation experiments, and carry out error analysis given the obtained experimental results \(d'\), that is, the maximum value of thin-wall deformation and the predicted value \(d\), and set the relative error as \(\delta\). The results are listed in Table 3.

Table 2 Orthogonal experiment results

| Groups | Cutting speed \(V_c\) (r/min) | Feed rate \(f\) (μm/z) | Depth of cut \(a_p\) (μm) | \(d\) (μm) |
|--------|-----------------|-----------------|-----------------|--------|
| 1      | 1000            | 2.5             | 10              | 12.79  |
| 2      | 1000            | 5               | 5               | 5.18   |
| 3      | 1000            | 7.5             | 2               | 1.67   |
| 4      | 3000            | 2.5             | 10              | 8.59   |
| 5      | 3000            | 5               | 5               | 2.65   |
| 6      | 3000            | 7.5             | 2               | 1.87   |
| 7      | 5000            | 2.5             | 5               | 5.49   |
| 8      | 5000            | 5               | 10              | 9.89   |
| 9      | 5000            | 7.5             | 2               | 1.85   |
| K1     | 19.64           | 26.87           | 31.27           |        |
| K2     | 13.11           | 17.72           | 13.32           |        |
| K3     | 17.23           | 5.39            | 5.39            |        |
| R      | 6.53            | 21.48           | 25.88           |        |

Table 3 Error Analysis

| Group | Cutting speed \(V_c\) (r/min) | Feed rate \(f\) (μm/z) | Depth of cut \(a_p\) (μm) | \(d'\) (μm) | \(d\) (μm) | \(\delta\) (μm) |
|-------|-----------------|-----------------|-----------------|---------|---------|---------|

4
From the error analysis in Table 3, it is deduced that the relative errors of the experimental results and the predicted values obtained by the three groups of different cutting parameters are 30.63%, 12.46%, and 23.25% respectively. The reason accounting for the error may be that there is no support of empirical formulas. It is difficult to guarantee the accuracy of the prediction results through linear fitting. However, the experimental data has the same trend, and it is feasible to describe the thin-wall cutting characteristics of flexible joints. This model can be used to qualitatively analyze the influence of cutting parameters on thin-wall deformation, and guide the subsequent thin-wall cutting process optimization.

3.2 Cutting force and deformation analysis

Whether the thin-wall cutting material model can truly reflect the elastoplastic deformation law of the material will impact the thin-wall deformation and cutting force simulation results. Therefore, the thin-wall deformation and cutting force under different JC constitutive models should be investigated. Using the cutting parameters of the first group in Table 2, taking the JC constitutive parameters as the influencing factor, the stress cloud diagram when the tool is processed to the thin-walled area is extracted for analysis, as illustrated in Figure 3. It is identical to the actual cutting. The four sets of simulation results all have stress concentration in the first and second deformation zones. The surface roughness of the workpiece is relatively small when the upper and lower sides are processed, while the surface roughness of the thin-walled part in the middle is relatively large.

![Figure 3. Stress diagrams under different JC constitutes](image)

A mechanical model is established in the machining process, set the cutting force when the tooltip point is machined to the top surface $L$ in the vertical direction as $F_x$, and decompose the cutting force $F \text{ into the cutting force in the X direction as } F_x$ and the cutting force in the Y direction is $F_y$, and in a
cutting process, the cutting force $F$ at the midpoint of the arc of the tooltip is taken as the ordinate and time $t$ is the abscissa. The result yielded by extracting four sets of different JC constitutive parameters is drawn, as illustrated in Figure 4.

Figure 4(b) shows that all groups' cutting force fluctuation range tends to first become smaller and then become larger. The reason is that the workpiece discontinuously reaches the separation criterion and is cut off, making the tool force discontinuous [8]. Moreover, the JC constitutive parameter mainly affects the average value of the cutting force, and has a negligible effect on the law of cutting force fluctuations. The shape of the workpiece and the cutting amount are the main factors that affect the law of cutting force fluctuations.

Figure 5. Relationship between cutting force and deformation

The deformation $\Delta x$ and $F_x$ of the thinnest point along the X direction is taken in the thin-walled region for analysis, as shown in Figure 5. Under different JC constitutes, it can be found that the time when $\Delta x$ increases to the maximum in the negative direction of X and the time when $F_x$ is zero, that is, the time for machining to a thin wall, time denoted by $t$ always exists, which means that when the tool is processed to thin before the thinnest point of the wall, the thin wall has reached the maximum deformation value. A conjecture can be put forward: the largest deformation of the thin wall is not at the thinnest part of the thin wall, but at a certain position in the direction of the thin wall processing.

The experimental verification selected the research results of Zhang Chaoxiao[2]. The processing of flexible joint Thin-walled structure was carried out on the micro-small turning-milling composite machining machine CSKM25-Ⅲ independently developed by Beijing Institute of Technology, using cemented carbide boring tool, at a cutting speed of $V_c=4500r/min$, a feed rate of $f=1.5mm/min$, a cutting depth of $a_p=0.05mm$, and the Thin-walled structure obtained by machining are magnified as depicted in Figure 6(a). Figure 6(a) shows that the maximum thin-wall deformation is about $90.3\mu m$ in the thin-wall machining direction. Among the four sets of constitutive parameter results, the simulation results yielded by using the constitutive parameters obtained by Li et al. are closer to the experimental results, as illustrated in Figure 6(b). Both the experiment and simulation results prove the conjecture that the maximum deformation place is close to the thin-walled part in the thin-walled machining direction, which provides guidance for the simulation and process optimization of the Thin-walled structure cutting process.
4. Conclusion

Based on the ABAQUS software, the simulation model for the fine boring process of flexible joints was established, considering the different JC constitutive parameters obtained by different experimental methods for flexible joint materials. And the orthogonal experiment method to carry out numerical simulation calculations was investigated, which fitted the prediction model of thin-wall deformation and cutting parameters. The influence of JC constitutive parameters on Ti6Al4V thin-wall deformation was explored. The research has reached the following conclusions:

1) JC constitutive parameters mainly affect the average value of the thin-wall cutting force, and have insufficient effect on the law of cutting force fluctuations.

2) Before the tool is processed to the thinnest point of the thin wall, the thin wall has reached the maximum deformation value. The maximum deformation of the workpiece is near the thin wall in the thin-wall machining direction.

3) In the study of thin-wall deformation of flexible joints, the constitutive parameters obtained by Li et al. are closer to the experimental results.

In future research, a more accurate deformation prediction model can be constructed based on the experimental data in this paper. This model would compensate for the deformation of key parts of thin-walled structures. Moreover, the method is popularized in the production and processing of more difficult-to-machine low-rigidity parts.

References

[1] Xu, L.Y., Li, B.Z., Yang, J.G.(2019) Simulation Analysis and Experimental Research on Micro Feature Grinding of High Elastic Alloy Steel 3J33 Considering Hardness. China Mechanical Engineering, 30(01):17-21.
[2] Zhang, C.X.(2015) Research on Key Processing Technology of Flexible Joints. Beijing Institute of Technology, Beijing.
[3] Zhou, C.L.(2017) Research on the Influence of Constitutive Model Parameters on the Simulation of Cutting Process. Modern manufacturing engineering, 1:105-109.
[4] Leseur, D. (1999) Experimental investigations of material models for Ti-6Al-4V and 2024-T3. Lawrence Livermore National Lab, San Francisco.
[5] Calamaz, M., Coupard, D., Girot, F. (2008) A new material model for 2D numerical simulation of serrated chip formation when machining titanium alloy Ti-6Al-4V. J Mach Tools Manuf 2008, 48:275–88.
[6] Johnson, G.R. (1985) Strength and fracture characteristics of a titanium alloy (.06al,.04v) subjected to various strains, strain rates, temperatures and pressures. Nav Surf Weapons Cent NSWC TR:86–144.
[7] Özel, T., Karpat, Y. (2007) Identification of constitutive material model parameters for high-strain rate metal cutting conditions using evolutionary computational algorithms. Mater Manuf
[8] Li, Z.X., Zhang, H.Q., Wang, Y.C. (2021) Finite element simulation of 40CrNi4Mo1V steady cutting process based on ABAQUS. New technology and new process, 1:31-37.

[9] Ye, G.G., Xue, S.F. (2019) Thermal gradient and its contribution to size effect of specific cutting energy. The International Journal of Advanced Manufacturing Technology, 101:2327–2339.

[10] Zang, J., Zhao, J., Li, A., Pang, J. (2018) Serrated chip formation mechanism analysis for machining of titanium alloy Ti-6Al-4V based on thermal property. J Adv Manuf Technol, 98:119–127.

[11] Xu, J., Mansori, M. (2016) Cutting modeling of hybrid CFRP/Ti composite with induced damage analysis. Materials (Basel):9.

[12] Yang, Y., Chen, Y., Gao, W. (2020) Experimental Research on the Influence of Three Elements of Cutting on the Deformation of Titanium Alloy Thin-walled Parts. Mechanical Research and Application, 33(05):61-64.

[13] Yaich, M., Ayed, Y., Bouaziz, Z., Germain, G. (2017) Numerical analysis of constitutive coefficients effects on FE simulation of the 2D orthogonal cutting process: application to the Ti6Al4V. Adv Manuf Technol 2017,93:283–303.