Experimental study on the reduction of process-induced deformation when milling a low stiffness structure made of Ti6Al4V titanium alloy

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Abstract
Large-scale slender beam structures with low stiffness are widely used in the aviation field. There will be a great deformation problem in machining because the overall stiffness of slender beam parts is lower. Firstly, the cutting mechanism and stability theory of the Ti6Al4V material are analyzed, and then the auxiliary support is carried out according to the machining characteristics of the slender beam structure. The feasibility of the deformation suppression measures for the slender beam is verified by experiments. The experimental analysis shows that on the basis of fulcrum auxiliary support, the filling of paraffin melt material is capable of increasing the damping of the whole system, improving the overall stiffness of the machining system, and inhibiting the chatter effect of machining. This method is effective to greatly improve the accuracy and efficiency during machining of slender beam parts. On the premise of the method of processing support with the combination of fulcrum and paraffin, if the tool wear is effectively controlled, the high precision machining of large-scale slender beams can be realized effectively, and the machining deformation of slender beams can be reduced.

Keywords Large-scale slender beam · Deformation · Auxiliary support · Titanium alloy

1 Introduction
Titanium alloy is one of the main materials of the whole structure of aviation. With the development of aviation technology in recent years, the application of titanium alloy materials in high maneuvering aircraft has been widely popularized. Ti6Al4V material is mainly used to make mechanical structure of aviation products, such as frame, impeller, wing plate, and beam structure. However, there are still some technical problems in the application of titanium alloy materials for processing of large-scale slender beam structure at home and abroad and, for example, serious deformation is the most common problem encountered during machining [1, 2]. Although the design of slender beam structure has many advantages, when the workpiece is removed from the fixture, deformation such as bending, twisting, or combined bending and torsion often occurs during machining due to its large aspect ratio, high material removal rate, and poor rigidity, which makes it difficult for the parts to meet the design requirements.

The Nervi S of the USA established a mathematical prediction model of machining deformation caused by initial residual stress of blank, and studied the relationship between structural deformation and the distribution state of initial blank stress [3]. Keith studied the influence of residual stress on machining deformation. Results indicated that the machining stress was closely related to the radius of arc tip and the radius of blunt circle of cutting edge. For aeronautical thin-walled structure, the machining residual stress had a certain effect on the machining deformation of workpiece [4]. Tlusty proposed the effective use of unprocessed parts as support, and explored the method of milling path optimization using the overall rigidity of aeronautical structural parts [5]. Zhang Feihu made a deep research on the cutting deformation mechanism and cutting mechanics model in machining theory [6, 7]. Huang Yunlin identified suitable cutting parameters using stable leaf flap simulation for the rough and finish machining of housing cavity, and verified the technical effectiveness of machining of thin-walled parts for the whole impeller from the aspects of blank and tool selection, fixture design, machining process
flow of integral impeller, NC program compilation and simulation, specimen processing, and measurement, ensuring feasible mass milling of thin-walled parts with high efficiency, high quality, and low cost [8]. Wang Ming selected the cutting parameters of stable point by MATLAB simulation. The results showed that the stability analysis method made the reasonable selection of cutting parameters possible which could avoid the occurrence of chatter, thus improving the machining quality and efficiency of thin-walled parts [9]. Dong Guojun, Harbin University of Technology, has carried out molecular dynamics simulation and experimental research on tool wear mechanism, and studied tool wear mechanism according to the change of chemical composition of tool tip, which provides technical support for cutting tool wear [10].

Although many scholars at home and abroad have done a lot of academic research in thin walls with low stiffness, impellers, and frame parts, there is little research on the machining deformation of slender beam parts with large-scale aspect ratio, and a breakthrough is needed in this direction. Processing a slender beam structure becomes difficult because it will be in the cantilever state and deformation and chatter will occur during machining. Therefore, the paper takes the slender beam structure with low stiffness as a research object and studies a method to suppress the deformation occurred during processing. In addition, experiments are performed to further study the deformation behavior of a cantilever structure with low stiffness during processing by considering the properties of Ti6Al4V. The clamping method of the slender beam structure is studied to improve the overall machining stiffness and damping to make it stable. Based on the optimal clamping mode, the influence of different tool wear and milling parameters on the machining deformation of low stiffness slender beam is explored, which provides technical support for the machining technology and clamping method of typical slender beam parts with low stiffness.

2 Theoretical analysis of cutting mechanism and milling stability of Ti6Al4V

2.1 Cutting mechanism analysis

The chip formation process of metal machining is actually the deformation process of material cutting layer. The chip separation process can be roughly divided into the first deformation zone (shear slip), the second deformation zone (fibrosis), and the third deformation zone (fibrosis and work hardening). As shown in Fig. 1a, the first deformation zone interacts with the second deformation zone. When the friction force of the knife surface is large, the chip discharge is not smooth, the extrusion deformation intensifies, and the shear slip deformation in the first deformation zone increases. In the contact area between the machined surface and the rear tool surface, due to the extrusion friction between the tool edge circle and the rear tool surface, the machined surface is fibrosis and work hardening, thus forming the third deformation zone [1].

Burr is a part of the edge area of the workpiece, which is a part of the chip removal in theory. It is a part of the machining process. The definition of burr parameters is an important standard for burr study and evaluating the energy consumption of deburring. The basic parameters of burr are usually studied by arbitrary cross section of burr. The main parameters of burr are height, root thickness, and root radius. As shown in Fig. 1a, burr height H refers to the maximum distance between the ideal end face of the workpiece terminal surface measured on the cross section and the profile of the burr cross section. Burr root thickness W refers to the distance from the plastic deformation convex starting point to the ideal surface of the workpiece measured on the end surface of the workpiece. The radius of the burr root circle is the radius of curvature of the root geometric curve of the burr cross section measured on the cross section. Obviously, the size of burr height H directly affects the dimensional accuracy and shape accuracy of the workpiece, while the thickness of burr root W has a relation to the efforts of deburring. By using characteristic parameters H and W, the specific size and shape of burr cross section can be expressed [11].

The cutting temperature produced by the milling cutter in the machining process can simplify the three-dimensional cutting into a simple two-dimensional plane oblique angle cutting, that is, the milling cutter can be separated into countless units along the spiral cutting line. The cutting process of a single unit is simplified diagonal cutting. Figure 1b is a simplified diagram of milling temperature model. The milling temperature is mainly from three regions: (1) The cutting temperature region of the front cutter surface caused by friction between the chip and the front cutter surface; (2) the cutting temperature region of the rear cutter surface produced by the friction between the rear cutter surface and the workpiece; and (3) temperature region of plastic deformation of shear surface produced by shear slip of metal plastic deformation [12].

As shown in Fig. 1c, the action of the arc radius of the tool resulted in a triangular region where tensile stress and extrusion stress combined on the workpiece when cutting. The grains in this region were elongated along the Y-axis due to stretching, and plastic shortened along the X-axis because of compression, finally forming a residual tensile stress under the action of these two behaviors. Consequently, the third deformation zone was formed in the workpiece, and the friction force Fx and normal force Fy acted on the surface layer of the workpiece. The normal force caused plastic deformation on the surface layer in the direction of Y-axis while the friction force Fx induced the surface layer to produce plastic deformation along the X-axis direction, which led to residual compressive stress on the machined surface [13].
2.2 Dynamic milling force model

As shown in Fig. 2, the milling system can be simplified into two “spring-damping” systems with vertical degrees of freedom. Considering the influence of the wavy surface left by the rake teeth, the instantaneous rigid force model is adopted for the rake teeth. The mathematical model of dynamic milling stability is the basis for the study of machining process stability and dynamic machining error.

The milling dynamics equation can be expressed as a differential equation

\[
\begin{align*}
mx \ddot{x} + cx \dot{x} + kx x &= \sum_{j=1}^{N} F_{xj}(t) \\
m_y \ddot{y} + cy \dot{y} + ky y &= \sum_{j=1}^{N} F_{yj}(t)
\end{align*}
\]  

(1)

where \(m_x, m_y\) — Quality of milling system in X, Y direction (kg);
\(c_x, c_y\) — Damping of milling system in X, Y directions (Ns/m);
\(k_x, k_y\) — Stiffness of milling system in X, Y direction (N/m);
\(F_{xj}, F_{yj}\) — Cutting force component (N) in X and Y direction acting on cutter teeth \(j\).

Figure 3 shows the force distribution of milling cutter blade, in which the \(F_t\) is tangential cutting force and the \(F_r\) is radial cutting force. In the milling process, the machining system is excited by the milling force in the \(X\) and \(Y\) directions, resulting in the corresponding dynamic displacement \(x\) and \(y\). Coordinate transformation of dynamic displacement in cutting thickness direction of cutter teeth \(v_\varphi = x \sin \varphi + y \cos \varphi\). As the
two-dimensional static cutting thickness has nothing to do with the mechanism of regenerative chatter, it can be ignored in the flutter stability analysis. So, the two-dimensional dynamic cutting thickness can be expressed in the following formula [10].

\[ h_j(\varphi) = (x-x_0)\sin\Omega t + (y-y_0)\cos\Omega t \]  

where \((x, y)\) represents the dynamic displacement of the current tool tooth period, and \((x_0, y_0)\) represents the dynamic displacement of the former tool tooth period. The rotation angular velocity of the spindle is \(\Omega \text{rad/s}\). Then, the radial contact angle \(\varphi_j\) is transformed into \(\Omega t\) with time. \(\varphi=(j-1)\varphi_p+\varphi\) is the instantaneous radial contact angle of cutter tooth \(j\). Since the number of cutting edges \(j\) is 4, the cutting angles of the four cutting edges are \(\varphi_0 = \varphi, \varphi_1 = \varphi+\pi/2, \varphi_2 = \varphi+\pi, \varphi_3 = \varphi+3\pi/2\).

The tangential cutting force \(F_t\) and the radial cutting force \(F_r\) of acting on the cutter tooth \(j\) are [10]

\[ F_t = K_t a_p h(\varphi) \quad F_r = K_r F_0 \]  

where \(a_p\) is axial tangential depth (mm); \(K_t, K_r\)—tangential and radial cutting force coefficients, respectively (N/m).

The total cutting force acting on the tool is

\[ F_x = \sum_{j=0}^{N_f-1} F_{tj}(\psi_j); \quad F_y = \sum_{j=0}^{N_f-1} F_{rj}(\psi_j) \]

Finally, we substitute formula (2) and (3) into formula (4) and express them in the form of matrix

\[
\begin{bmatrix}
F_x \\
F_y
\end{bmatrix} = \frac{1}{2} a_p K_1 [A] \begin{bmatrix}
\Delta x \\
\Delta y
\end{bmatrix}
\]

where \(\Delta x=(x-x_0), \Delta y=(y-y_0)\), \([A] = \begin{bmatrix}
\alpha_{xx} & \alpha_{xy} \\
\alpha_{yx} & \alpha_{yy}
\end{bmatrix}\)

\[\alpha_{xx} = \sum_{j=0}^{N_f} g_j \sin^2 \varphi_j K_t (1+\cos 2\varphi_j) \]
\[\alpha_{xy} = \sum_{j=0}^{N_f} g_j \cos^2 \varphi_j K_t \]
\[\alpha_{yx} = \sum_{j=0}^{N_f} g_j \sin^2 \varphi_j K_r \]
\[\alpha_{yy} = \sum_{j=0}^{N_f} g_j (1+\cos 2\varphi_j) K_r \sin 2\varphi_j \]

Considering the variation of these parameters with time and angular velocity, Eq. (6) is expressed in matrix form in time domain as follows

\[ \{ F(t) \} = \frac{1}{2} a_p K_1 [A(t)] \{ \Delta(t) \} \]

where \(A(t)\) is a periodic function of \(\omega=NT\) and \(T=2\pi/\omega\). The expansion form of Fourier series is

\[ [A(t)] = \sum_{n=0}^{\infty} [A_n] e^{i\omega nt} \quad [A_n] = \frac{1}{T} \int_0^T [A(t)] e^{-i\omega nt} dt \]

Ignore the influence of higher harmonics and retain the DC component \(A(0)\)

\[ [A(0)] = \frac{1}{\varphi_p} \int_{\varphi_p}^{\varphi_p} [A(\varphi)] d\varphi = \frac{N}{2\pi} [A] \]

where \([A] = \begin{bmatrix}
\alpha_{xx} & \alpha_{xy} \\
\alpha_{yx} & \alpha_{yy}
\end{bmatrix}\)

By substituting Eq. (8) into Eq. (6), the expression of dynamic milling force coefficient can be simplified as

\[ \{ F(t) \} = \frac{1}{2} a_p K_1 [A_0] \{ \Delta(t) \} \]

2.3 Flutter stability limit

As shown in Fig. 2, a tool-workpiece system can be simplified to X and Y two-degree-of-freedom vibration systems in two vertical directions [11]. Let the frequency response function of the tool workpiece system be
\[ [G(i\omega)] = \begin{bmatrix} G_{xx}(i\omega) & G_{xy}(i\omega) \\ G_{yx}(i\omega) & G_{yy}(i\omega) \end{bmatrix} \]

Where \( G_{xx}(i\omega) \) and \( G_{yy}(i\omega) \) represent the direct frequency response functions of the tool workpiece system in X and Y directions respectively. \( G_{xy}(i\omega) \) and \( G_{yx}(i\omega) \) represent the cross frequency response functions of the tool workpiece system in X and Y directions respectively. Let the relative vibration vectors of the tool and the workpiece at the current time \((t)\) and the previous cutting time \((t-T)\) be

\[
\{r\} = \{x(t)y(t)\}^T \\
\{r_0\} = \{x(t-T)y(t-T)\}^T
\]

The frequency domain of the relative vibration function of the tool and workpiece at the current time and the cutting time of the previous cutter tooth at flutter frequency \(i\omega_c\) is expressed as [14]

\[
\begin{align*}
\{r(i\omega_c)\} &= [G(i\omega_c)]\{F\} \exp(i\omega_c t) \\
\{r_0(i\omega_c)\} &= \exp(-i\omega_c t)\{r(i\omega_c)\}
\end{align*}
\]

Regenerative displacement

\[
\{\Delta(i\omega_c)\} = \{r(i\omega_c)\} - \{r_0(i\omega_c)\} = \left[1 - \exp(-i\omega_c t)\right]e^{i\omega_c t}[G(i\omega_c)]\{F\}
\]

Let the determinant be zero, find the special solution of the equation, and the characteristic equation of the tool workpiece closed-loop dynamic system is

\[
\det\left\{[I] - \frac{1}{2}a_2K_{ic}(1 - \exp(-i\omega_c t)) [A_0][G_0(i\omega_c)]\right\} = 0
\]

Where \( K_{ic} \) is the tool radial shear force coefficient. The characteristic equations obtained by further simplification are as follows:

\[
\det\{[I] + \Lambda[G_0(i\omega_c)]\} = 0
\]

The eigenvalues can be obtained by neglecting the influence of the cross functions \( G_{xy} \) and \( G_{yx} \):

\[
\Lambda = -\frac{1}{2a_2} \pm \frac{1}{2a_2} \sqrt{a_1^2 - 4a_0}, \quad a_{01} \text{ among }
\]

Fig. 4 Factors influencing deformation of slender beam parts with low stiffness

Fig. 5 Schematic illustration of deformation effect of auxiliary support
Its eigenvalues contain real and imaginary parts because the transfer function is plural. As the axial cutting depth is real number, by substituting $A=\Lambda_R+i\Lambda_I$ and $e^{i\omega_c T}=\cos(\omega_c T)-i\sin(\omega_c T)$ into eigenvalues, the ultimate axial tangential depth at flutter frequency can be obtained [15]:

$$a_{\text{plim}} = \frac{2\pi}{NK_c} \left\{ \frac{\Lambda_R(1-\cos(\omega_c T)) + \Lambda_I\sin(\omega_c T) + i(\Lambda_I(1-\cos(\omega_c T)) + \Lambda_R\sin(\omega_c T))}{1-\cos(\omega_c T)} \right\}$$

(16)

where $K_c$ is the tool tangential shear force coefficient.

The upper imaginary part is zero because the axial cutting depth $a_p$ is a real number, and the final expression of ultimate axial depth can be simplified

$$a_{\text{plim}} = -\frac{2\pi \Lambda_R (1 + \kappa^2)}{NK_c}$$

(17)

It can be seen that if the flutter frequency $\omega_c$ is given, the limit axial cutting depth can be obtained according to the above formula, and

$$\kappa = \tan \psi = \tan \frac{\pi}{2} - \frac{\omega_c T}{2}$$

(18)

Where $\psi = \arctan \kappa$ is the phase shift of eigenvalue. $\varepsilon=\pi-2\bar{\psi}$ is the phase shift between internal and external modulation. Therefore, if the vibration ripple left by the cutting arc is an integer $k$, $\omega_c T = \varepsilon + 2k\pi$. The spindle speed can be obtained by calculating the cutting cycle $T$

$$n = \frac{60}{N(2k + 1)\pi - 2\tan^{-1}(\Lambda_I/\Lambda_R)}$$

(19)

### Table 1 Experimental conditions

| No. | Name                        | Details                                                                 |
|-----|-----------------------------|-------------------------------------------------------------------------|
| 1   | NC Machining Center         | Tool type: 6 mm diameter, 4 edges, 45° helix angle. The surface is coated with TiSiN cemented carbide end mill. The clamping suspension is 30 mm. |
| 2   | Paraffin wax                |                                                                         |
| 3   | 3D edge seeker(The accuracy is 0.002mm) |                                                                         |
| 4   | Micrometer                  |                                                                         |
| 5   | Size of titanium alloy blank| Length 440 mm × width 12 mm × height 12 mm                            |
| 6   | Dimension of slender beam   | Length 420 mm × width 8.6 mm × height 8.6 mm                           |
| 7   | Processing cooling mode     | Cutting fluid assisted cutting                                          |
| 8   | Residual stress measuring instrument | Measuring angle: 0°, ± 15°, ± 45°, ± 60°                                |
| 9   | Processing support of slender beam with low stiffness | Fulcrum support                                                          |
| 10  | No auxiliary support        |                                                                         |
| 11  | Paraffin assisted support   |                                                                         |
| 12  | Fulcrum+Paraffin auxiliary support |                                                                         |
| 13  | On the basis of the above optimal machining support mode, cutting parameters are selected as variables for cutting deformation experiment. | Spindle speed(ε/min): 4000, 8000, 12000, 16000; Feed rate(ε/min): 200, 400, 600, 800; Cutting depth (mm): 0.02, 0.04, 0.06, 0.08 |

**Fig. 6** Experimental environment of slender beam processing.
It can be concluded that in order to improve the cutting stability, the high precision parts can be processed by increasing the damping and the overall stiffness of the machining system as well as reducing the cutting force.
3 Deformation control measures and processing experiment of slender beam

3.1 Influencing factors and restraining methods of processing deformation of slender beam with low stiffness

For the deformation problems of low stiffness parts, the influencing factors of deformation in the processing of suspension beam parts with low stiffness need to be investigated first, as shown in Fig. 4. It is found that the problems of low stiffness and deformation can be effectively solved by increasing the overall machining stiffness of low stiffness parts and the damping of the system. At the same time, tool wear and machined surface stress can be improved.

The clamping mode of low stiffness parts is the most important factor that directly influence the machining accuracy of such parts. When clamping slender beam parts with low stiffness, pressure plate clamping is not recommended because the special suspension state of the parts will cause the parts to be subjected to cutting force during the machining process, and hence the suspension deformation will occur because of the low stiffness. Upon unloading, even if the condition of the parts after machining is satisfied, the machined parts will suffer deformation due to the release of the external clamping force. Therefore, it is necessary to ensure the overall processing stiffness of the parts during processing, so that it not only can enable the stable clamping of the parts, but also improve the stiffness of the overall workpiece processing system. To achieve this, the auxiliary support is necessary for the cantilever parts aiming to inhibit the chattering or deformation phenomenon occurs during machining. On the other hand, paraffin filling is carried out on the basis of auxiliary support to indirectly increase the damping of the workpiece processing system, which is capable of further improving the machining accuracy. The filling of paraffin melt can make it possible to suppress chatter in the process of machining, thereby greatly improving process efficiency. Figure 5 shows the effect of deformation with or without auxiliary support.

3.2 Experimental scheme of deformation of slender beam with low stiffness

In this experiment, the clamping methods of the slender beam are designed with no auxiliary support, fulcrum auxiliary support, paraffin auxiliary support, and fulcrum + paraffin auxiliary support. The number of fulcrum is divided and increased according to the length of suspension beam. The processing deformation scheme of slender beam with low stiffness is shown in Table 1. The experimental environment is shown in Figure 6.

3.3 Influence of processing support mode on deformation of slender beam with low stiffness

The cutting parameters are \( n = 4000 \) r/min, \( F = 800 \) mm/min, and \( a_p = 0.02 \) mm. At the end of the experiment, the deformation of the workpiece in Z and Y directions was measured online by 3D edge finder. A micrometer was used to measure machining dimension of parts. When measuring the
deformation of slender beam, mark the maximum deformation and measure the surface residual stress with residual stress measuring instrument. Table 2 is the experimental data of processing deformation of the slender beam with low stiffness, and Figure 7 is the influence curve of processing method on the deformation of the slender beam.

It can be seen in Figure 7 and Table 2 that chatter occurred and sharp squeal was produced if the slender beam was machined without auxiliary support, indicating that the chatter was severe during cutting. The reason for the large deviation is that the deformation of slender beams without auxiliary support occurred. From the data in Table 2, it is observed that as compared to the chatter phenomenon of the slender beam processed without no auxiliary support, this behavior was gradually improved when processing the beam with two-fulcrum auxiliary support, the chatter pattern on the surface was gradually reduced, and the deformation and dimension deviation occurred during machining of the slender beam were gradually improved. Moreover, the residual stress at the maximum deformation becomes smaller after machining. It shows that the unstable chatter phenomenon can be improved and the residual stress is reduced and the machining deformation of slender beam parts can be reduced by upgrading the clamping mode and using the fulcrum support method. When the number of fulcrum was increased to 4, the degree of deformation and machining accuracy of slender beams were controlled within 0.03 mm. Although the fulcrum auxiliary support is an effective option to improve the machining accuracy of the slender beam, the combination of fulcrum and paraffin clamping processing can further optimize the machining accuracy. An increase in the number of paraffin and fulcrum provides an opportunity to reduce the deformation and improve the processing accuracy of the slender beam and the residual stress at the maximum deformation of the slender beam after processing is also significantly reduced. When the processing mode was molten material combined with four fulcrums, the dimensional accuracy of beam was 0.016 mm, and the deformation was less
than 0.01 mm. From the comparative experiments of 10 clamping methods, it is found that in order to improve the overall processing stiffness and system damping, using the clamping method of the combination of molten material and fulcrum is a breakthrough to realize the machining of large-scale slender beams.

Fig. 9 Influence curve of milling parameters on machining deformation of slender beam

Fig. 10 3D model of typical slender beam with low stiffness
3.4 Influence of tool wear on machining deformation of slender beam with low stiffness

The optimal processing support mode was selected from the previous experimental results: four fulcrums + paraffin auxiliary support. The machining experiments of the slender beam with low stiffness were carried out by using different worn tools. The cutting parameters are \( n = 4000 \, \text{r/min} \), \( F = 800 \, \text{mm/min} \), and \( a_p = 0.02 \, \text{mm} \). At the end of the experiment, the deformation of the workpiece in Z and Y directions was measured online by 3D edge finder. A micrometer was employed to measure machining dimension of parts. Figure 8 shows the curve of machining deformation of slender beam.

It is seen from the data in Figure 8 that tool wear had a great influence on the machining accuracy of the slender beam. The increasing tool wear caused the machining deformation and dimensional deviation of the slender beam to increase. The deformation and machining accuracy of the slender beam were within 0.05 mm. It can also be observed in the table and the figure that if the tool wear was effectively controlled, the machining accuracy and deformation of the slender beam could be effectively improved. The reason to achieve such a high-precision processing is that the experimental processing support method improves the overall processing rigidity of the slender beam, and the paraffin also indirectly improves the damping of the processing system and suppresses the chatter phenomenon. Therefore, the experimental results show that under the premise of four fulcrum and molten material processing support mode, the high-precision processing of large-scale slender beam can be effectively realized if the tool wear is effectively controlled, and hence the processing deformation of the slender beam can be reduced [16].

3.5 Influence of milling parameters on machining deformation of slender beam with low stiffness

The best processing support mode was selected four fulcrums + paraffin auxiliary support. At the end of the experiment, the deformation of the workpiece in Z and Y directions was measured online by 3D edge finder. A micrometer was used to measure machining dimension of parts. Figure 9 shows the influence of milling parameters on machining deformation of the slender beam.

It can be seen in Figure 9 that with the increase of the spindle speed, the machining deformation of the slender beam was gradually reduced, and the machining dimensional accuracy was also gradually improved. However, an increase in feed speed and cutting depth caused the machining dimensional accuracy to become worse. The graph illustrates that the cutting depth has a great impact on the machining deformation of the slender beam while the spindle speed and feed speed have a certain regular influence on the deformation, the change was relatively flat. Although high-speed milling has excellent machining effect on the surface quality of titanium alloy materials, severe tool wear can be observed when high speed milling of titanium alloy. Therefore, high speed milling is suggested to be used for the finishing process of the slender beam, which not only can effectively control the tool wear, but also improve the machining accuracy of parts [17].

4 Machining verification of Ti6Al4V typical slender beam with low stiffness

Figure 10 shows the 3D model of the typical slender beam with low stiffness to be machined. The model parts are verified by the previous experiments. After the processing, the dimension of the slender beam was measured to evaluate the machining accuracy.

1. Milling process of slender beam with low stiffness

Being similar to the processing of ordinary structural parts, it is necessary to analyze the drawings of the parts and determine the process flow. Figure 11 is the process flow chart.

2. Fixture design

Fig. 11 Process flow chart

Fig. 12 Fixture for slender beam parts
According to the clamping experiment of titanium alloy structure parts with low stiffness, process and fixture design was carried out for typical low stiffness parts to meet the dimensional accuracy requirements, and repeated clamping operations can be avoided. As shown in Fig. 12, the fixture is provided with a pouring port and an air outlet for pouring liquid materials. The contact surface between the blank and the fixture is bonded with AB glue to avoid external force as much as possible, and reduce the clamping deformation caused by the release of the external force.

(3) CAM cutting strategy for milling low stiffness parts

CAM cutting strategy is as follows: the outer profile milling path is from the outer edge to the inner ring milling, and the depth is first. The milling path of the inner cavity is from the inner to the outer edge and the depth is first. The common cutting depth of each tool is constant; the milling tool needs to cut smoothly during machining to make the cutting state stable, and all tool paths of the tool must follow the arc feed path to prevent the deformation of parts due to overcutting. Avoid tool path repetition. Avoid unnecessary damage to workpiece surface caused by cutting tool during machining. The tool path extends a step on the edge to remove the edge burr. The CAM tool feeding strategy is shown in Figure 13.

As shown in Figure 14, the surface quality of the processed weak rigid parts is in good condition, the maximum deformation of the longest slender beam in the middle is 0.019 mm, the size deviation of the 420 mm × 8.6 mm × 8.6 mm slender beam in the middle is −0.017 mm, the machined surface is bright, and the roughness is less than 0.5 μm.

5 Conclusions

Aiming at the deformation problem of large-scale slender beam with low stiffness, this paper has carried out theoretical analysis on milling stability, and has performed experiments by adopting some methods to restrain the deformation. In the end, the processing of typical large-scale parts with low stiffness was verified. The conclusions are as follows:
(1) By changing the clamping method to increase the system damping and improve the overall stiffness of the processing system, the processing deformation of slender beam with low stiffness can be improved.

(2) When machining slender beam parts, the paraffin filling clamping method based on the fulcrum auxiliary support has a good effect of restraining machining chatter, which can greatly improve the machining accuracy and efficiency of slender beam parts.

(3) Under the premise of fulcrum and paraffin combined with auxiliary support method, as long as the tool wear is effectively controlled, the high-precision machining of large-scale slender beam can be effectively realized, and the machining deformation of slender beam can be reduced.

(4) Through the theoretical and technical support of the experimental scheme, the machining of typical large-scale slender beam with low stiffness can be realized.

Nomenclature  
- $m_c$: Quality of milling system in X direction (kg);
- $m_y$: Quality of milling system in Y direction (kg);
- $c_c$: Damping of milling system in X directions (Ns/m);
- $c_y$: Damping of milling system in Y directions (Ns/m);
- $K_{rx}$: Tool radial shear force coefficient;
- $K_{ry}$: Tool tangential shear force coefficient;
- $G_{c,i}(i\omega)$: Represent the direct frequency response functions of the tool workpiece system in X directions respectively;
- $G_{y,i}(i\omega)$: Represent the direct frequency response functions of the tool workpiece system in Y directions respectively;
- $G_{x,i}(i\omega)$: Represent the cross frequency response functions of the tool workpiece system in X directions respectively;
- $G_{y,i}(i\omega)$: Represent the cross frequency response functions of the tool workpiece system in Y directions respectively;
- $a_z$: Axial tangential depth (mm);
- $K_t$: Tangential cutting force coefficients (N/m);
- $K_n$: Radial cutting force coefficients, respectively (N/m);
- $k_s$: Stiffness of milling system in X direction (N/m);
- $k_y$: Stiffness of milling system in Y direction (N/m);
- $F_y$: Cutting force component in X direction acting on cutter teeth;
- $F_y$: Cutting force component in Y direction acting on cutter teeth;
- $\omega$: Flutter frequency

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Declarations

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