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ORIGINAL ARTICLE

Comparison and analysis of main effect elements of machining distortion for aluminum alloy and titanium alloy aircraft monolithic component

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Abstract Main effect elements of machining distortion for aluminum alloy and titanium alloy aircraft monolithic component are investigated by finite element simulation and experiment. Based on an analysis of milling process characters, finite element models of machining distortion are developed. Considering the action of initial residual stress, finite element simulation and analysis of machining distortion for aluminum alloy aircraft monolithic component are performed. Initial residual stress, cutting loads, and coupling action of these two effect factors are taken into account, respectively, to perform finite element simulations of machining distortion for titanium alloy aircraft monolithic component. The finite element simulation results are compared with experiment results and found to be in good agreement, indicating the validation of the proposed finite element models. The research results show that the initial residual stress in the blank is the main effect element of machining distortion for aluminum alloy aircraft monolithic component, while cutting loads (including cutting force and temperature) are the main effect element of machining distortion for titanium alloy aircraft monolithic component. To decrease machining distortion of aluminum alloy aircraft monolithic component, the initial residual stress in the blank must be controlled first. Similarly, to decrease machining distortion of titanium alloy aircraft monolithic component, the cutting loads must be controlled first.

Keywords Aluminum alloy · Titanium alloy · Aircraft monolithic component · Machining distortion · Effect element

Modern aviation is developing toward high-speed and heavy load. A lot of aircraft parts which were previously made as assemblies of thin-walled components can now be made as functionally equivalent, monolithic component which can reduce the airplane weight and enhance its strength [1]. Aluminum alloy and titanium alloy are primary two kinds of materials of aircraft parts. Aluminum alloy as a kind of important structural material is widely used in aerospace industry for its some superiority, such as small density, high mechanical strength, good plastic behavior, and corrosion-resistant characteristic. Titanium alloy has also been regarded as crucial material of modern aerospace industry because of its excellent mechanical properties, such as high strength-to-weight ratio, fighting against high temperature and corrosion resistance [2].

Many aircraft monolithic components, such as beam, bulkhead, and joint, have been made with aluminum alloy 7075 and titanium alloy Ti6Al4V. However, when oversize aircraft monolithic components are machined, in which the start-to-finish weight ratio for these components is easily 10:1 and greater, meaning that more than 90 % of the initial material is machined away, machining distortion are often produced. Machining distortion leads to great economic losses and has been one of the most striking problems that aircraft manufacturing industry has to face up to [3, 4].

Although some pretreatment have been done for the blank of aircraft monolithic component to decrease machining distortion, different technologies, different machining parameters, and different machining tools can cause different machining distortions. For example, with application of high-speed milling to a pocketed aircraft component which is 660 mm long, the distortion magnitude is very small, but it increases greatly to 5 mm when the common machining speed is used.

To eliminate aircraft monolithic component distortion, machining requires a fundamental understanding how

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Table 1 Mechanical and physical properties of aluminum alloy 7075

Temperature/°C	20	100	150	200	300
Elastic modulus/GPa	71	65.193	60.594	56.262	37.982
Plastic modulus/MPa	250	210	180	150	50
Yield strength/MPa	455.9	389.1	346.6	275.7	47.1
Thermal conduction coefficient/W/m°C	114.8	128.4	135.7	142.2	152.7
Specific heat/J/Kg°C	835.4	897	916.3	974	1,012.5

machining distortion develops during cutting process. A present study on machining distortion of monolithic component is mainly about surface dimensional error and machining distortion simulation. For the first aspect, the emphasis concentrates on not the whole machining distortion of parts, but local elastic distortion, and therefore, even the surface dimensional error meets the design criterion, the component will be discarded inevitably if large distortion happens after being finished [5–9].

For the second aspect, the relevant published research works about machining distortion simulation and analysis can be summarized as follows: Jitender et al. [10] studied the machining distortion of aircraft monolithic component by finite element simulation and experiment, and an optimization of cutting parameters, clamping schemes, and machining sequences were carried out. MSC Software Corporation [11] carried out the machining distortion simulation of aircraft monolithic component and took it as an example embedding FEA solver MARC. Yang et al. [12] developed a physics-based material process simulation to investigate the distortion of titanium alloy aircraft monolithic component during machining process by finite element method. Guo et al. [13] established a finite element model of the machining distortion for aluminum alloy multi-frame components and developed a software system used to predict machining distortion for aero-monolithic multi-frame components. Liu [14] developed the three-dimensional finite element model of a helical tool and a thin-walled part with a cantilever. Using this three finite element models, the milling process of a thin-walled part was simulated and analyzed. Zhang et al. [15] studied the machining distortion by finite element method. In this work, the machining deformation characteristics were analyzed and the simulation of different machining path was carried out. Bi et al. [16] built the finite element model of milling process considering the action of initial residual stress, cutting force, cutting heat, clamping, and machining path, and the machining distortion process for aluminum alloy aircraft monolithic component was simulated using this model. Dong et al. [17] studied the machining deformation of aluminum alloy aircraft monolithic component by finite element method and experiment on the basis of machining process simulation of a single tool tooth. The restart calculation was put forward in finite element simulation. Wang [18] set up a finite element model of machining distortion considering multifactors coupling effect. With this finite element model, the prediction and analysis of machining distortion for aluminum alloy aircraft monolithic component were performed.

To sum up, above research works mainly aim at machining distortion simulation and predicting based on finite element method. However, there is a lack of study on the cause and main effect element of machining distortion of aircraft monolithic component, particularly for titanium alloy aircraft monolithic component. The cause of machining distortion for titanium alloy aircraft monolithic component remains unknown by now.

For aluminum alloy and titanium alloy, there has been significant divergence with the material characteristic, and also, the machining technology and cutting parameters used to cut of these two kinds of materials are different, resulting in different machining distortion laws. At present, the comparison and analysis of main effect elements of machining distortion for aluminum alloy and titanium alloy aircraft monolithic component have not been reported.

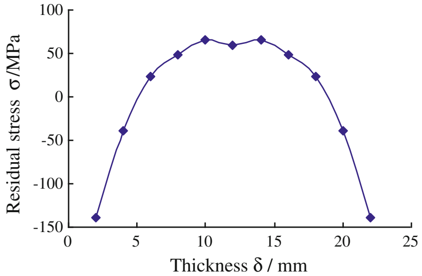


Fig. 1 Initial residual stress distribution in the blank

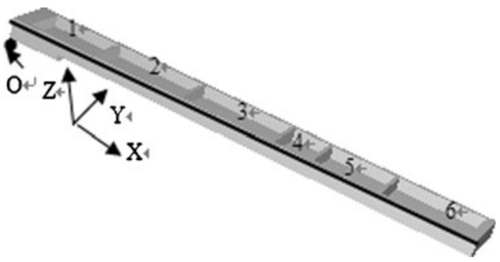


Fig. 2 Aluminum alloy aircraft monolithic component

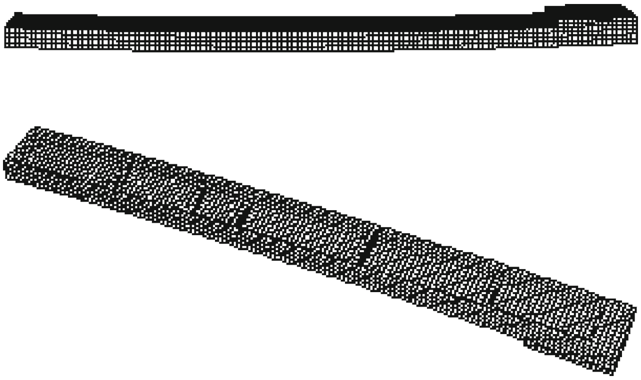


Fig. 3 Simulation result of machining distortion

In this paper, the aims of this research are to explore the main effect elements of machining distortion for aluminum alloy and titanium alloy aircraft monolithic component. Based on an analysis of milling process characters, the coupled thermomechanical finite element models are developed. The actions of initial residual stress, cutting loads (including cutting force and temperature), and coupling of these two effect factors are taken into account to perform finite element simulations. To verify the finite element simulations results, the machining distortion experiment are carried out. Further, the main effect elements of machining distortion for aluminum alloy and titanium alloy aircraft monolithic component are compared and analyzed, and the causes producing machining distortion for titanium alloy aircraft monolithic component are also investigated.

1 Analysis of machining distortion for aluminum alloy aircraft monolithic component

Machining distortion of aluminum alloy aircraft monolithic component was analyzed by finite element simulation and experiment. To study the effect of initial residual stress in the blank on machining distortion of aircraft monolithic component, when the analysis was performed, cutting loads (including cutting force and temperature) were not applied to the material removal process, only the corresponding mesh element being removed.

Table 2 Comparison of the simulation and measurement distortion values

Distance along length direction x/mm	50	80	160	200	260	320	380	410	480
Simulation value z/mm	1.44	2.06	3.32	3.65	3.77	3.44	2.66	2.06	0.46
Experiment value z/mm	1.54	2.18	3.60	3.82	3.95	3.63	2.80	2.30	0.52
Errors e%	6.5	5.5	7.8	4.4	4.6	5.2	5.0	10.4	11.5

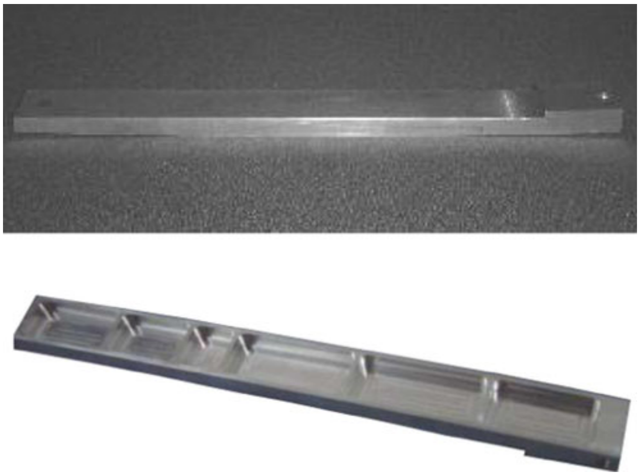


Fig. 4 Experiment result of machining distortion

1.1 Pretreatment of blank

The workpiece material was aluminum alloy 7075, classified as massive material, and the dimensions of length, width, and height are 500, 50, and 22 mm, respectively, which was presented with quenching and artificial aging treatment. The mechanical and physical properties of material are given in Table 1.

To get a blank with initial residual stress, a stress analysis of blank was carried out based on theoretical calculation as given in the literature [19]. Figure 1 shows the initial residual stress distribution along thickness direction in the blank, and Fig. 2 shows the designed shape of the workpiece.

1.2 Establishing of finite element model

Finite element model of aircraft monolithic component was established according to the actual shape of workpiece. The model was divided into 11 layers along the thickness direction and was meshed with eight nodes C3D8R element, with a total of 16,500 elements and 19,656 nodes. The residual stress curve from Fig. 1 was dispersed and solved based on the principle of force equilibrium and moment equilibrium. The mean stress of every layer obtained was applied to finite element model using the corresponding node command in finite element code ABAQUS.

1.3 Finite element simulation

Finite element simulation of machining distortion was performed using the commercial finite element code ABAQUS. The 3-2-1 constraint principle was adopted as the

Table 3 Mechanical and physical properties of titanium alloy Ti6Al4V

Temperature /°C	20	250	400	600	700	800	850
Elastic modulus/GPa	125	110	100	74	55	27	5
Yield strength/MPa	803.89	701.32	605.32	500.82	462.1	397.12	321.37
Thermal expansion coefficient /10^{-6}/•K	8.78	9.83	10.68	11.42	12.01	12.21	12.37
Thermal conductivity /W/m•K	6.8	8.7	10.3	13.72	16.23	17.31	17.86
Specific heat /J/Kg•K	611	653	691	749.3	812.4	896.3	932.5

boundary conditions, where the rigid motion of the workpiece was constrained, but the workpiece can be free to distort to reach a new stress equilibrium state [20]. Due to the machining environment was at room temperature (300 K), the initial workpiece temperature was set to room temperature. To realize finite element simulation of machining distortion, the removed element was laid in the same layer, which was removed when finite element simulation was carried out. Each time the layer was removed, the load step was calculated for a time in finite element code ABAQUS. During the finite element simulation, every frame of aircraft monolithic component was divided into six layers and the material of every frame was removed with machining for six times. In addition, the bottom was divided into three layers and the material in the bottom was removed with machining for three times. Thus, through the calculation of nine load steps, finite element simulation of machining distortion process for aluminum alloy aircraft monolithic component was completed.

1.4 Result analysis

Figure 3 shows the finite element simulation result of machining distortion. As can be seen from this graph, aluminum alloy aircraft monolithic component appears concave and bending distortion. After machining operation, due to the release and redistribution of residual stresses, the distortion of workpiece is caused, the law of which is bending distortion in the middle and warped at both ends. Some characteristic points along the length direction were picked up at intervals, and the distortion values of these characteristic points are listed in Table 2. It can be seen from the table that the bending distortion is quite obvious, and the maximum distortion value is 3.77 mm.

1.5 Experiment verification

To verify finite element simulation results, machining distortion experiment for aluminum alloy aircraft monolithic component was performed on a CNC machining center. During machining, workpiece sides were nipped by jaw vice. The cutting parameters used in experiment were given, including the spindle rotation speed of 2000 r/min, the 0.3 mm feed per tooth, the 3 mm radial cutting width, and the 0.5 mm depth of cutting. The slot miller whose diameter was 12 mm was adopted. The experiment result is illustrated in Fig. 4.

The distortion values of above characteristic points of machined workpiece were measured using tri-ordinate measuring machine and listed in Table 2. As can be seen from above Figs. 3 and 4 and Table 2, the machining distortion law from finite element simulation is in accord with experiment result, which appears bending distortion in the middle and warped at both ends. Moreover, finite element simulation and experiment have the same maximum bending distortion position. Based on the above comparisons and analyses, the finite element simulation result agrees well with the experiment result, validating, therefore, the proposed finite element model.

Because the finite element simulation of machining distortion did not take into account, the effect of cutting loads (including cutting force and temperature), therefore, according to the above finite element simulation and experiment studies, a conclusion can be drawn that the initial residual stress in the blank plays an important role in machining distortion, and it is the main effect element of machining distortion for aluminum alloy aircraft monolithic component. To control machining distortion of aluminum alloy aircraft monolithic component, the initial residual stress in the blank must be studied first.

Fig. 5 Initial residual stress distribution in the blank

Fig. 6 Titanium alloy aircraft monolithic component

2 Analysis of machining distortion for titanium alloy aircraft monolithic component

2.1 Pretreatment of blank

The workpiece material was titanium alloy Ti6Al4V, which was presented with annealing treatment and the dimensions of length, width, and height are 300, 30, and 11 mm, respectively. The bending radius of arc-shaped workpiece is 543 mm. The mechanical and physical properties of material are given in Table 3.

To get a blank with initial residual stress, based on the thermomechanical and elastic–plastic theories, an annealing analysis of titanium alloy blank was carried out using finite element method. Simultaneously, the residual stress experiment was conducted by combining layer removal method with X-ray diffraction method. An agreement between experiment and simulating results showed the anneal simulation analysis was reasonable, and the initial residual stress distribution of blank for titanium alloy aircraft monolithic component was obtained. The detailed analysis and application process for initial residual stress was given in the literature [21].

Figure 5 shows the initial residual stress distribution in the blank of titanium alloy aircraft monolithic component, and Fig. 6 shows the designed shape of the workpiece.

2.2 Establishing of finite element model

Finite element model of aircraft monolithic component was established according to the actual shape of workpiece. Based on an analysis of milling characters, an elastic–plastic finite element model was developed to simulate the milling process of titanium alloy monolithic component. In this model, the action of cutting tool was replaced by cutting loads (including cutting force and temperature), which were gained by cutting experiments and were fed into the finite element code ABAQUS to predict the dynamic behavior of workpiece during material removal. The finite element model was meshed with eight nodes C3D8R element.

2.3 Simulation and analysis

Machining processes of titanium alloy aircraft monolithic component was simulated using the commercial finite element code ABAQUS. The finite element simulation process was divided into two phases. One was the cutting stage where the clamps were applied, and the other was the stress inside the final part re-equilibrium stage where the clamps were removed. In the first cutting stage, the clamping condition accorded with the realistic machining condition and was converted into restriction of boundary condition. Due to the workpiece was fixed on the worktable of machine tool, so the degrees of freedom *x, y, z* of the workpiece bottom were constrained. In the second stage, the 3-2-1 constraint principle was adopted as the boundary conditions, where the rigid motion of the workpiece was constrained, but the workpiece can be free to distort to reach a new stress equilibrium state. Because the machining environment was at room temperature (300 K), the initial workpiece temperature was set to room temperature.

Active and deactive method provided by ABAQUS code was used to simulate material removal process, in which the stiffness matrix multiplied by a very small coefficient was set

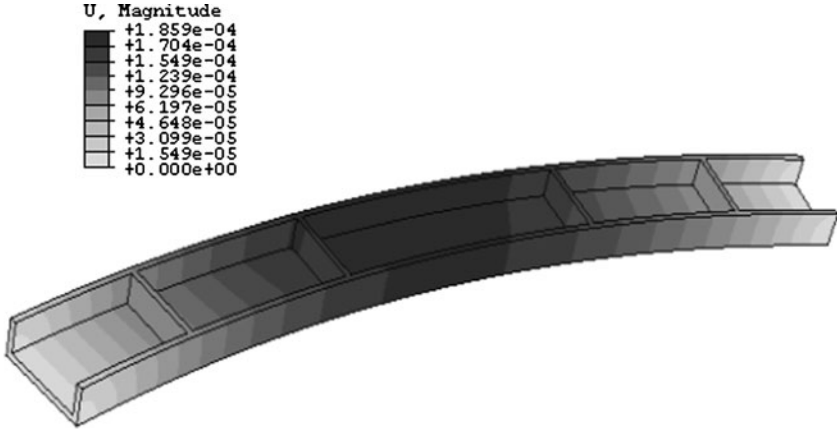


Fig. 7 Simulation result of machining distortion only considering initial residual stress

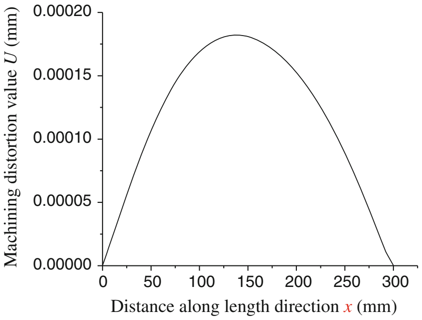


Fig. 8 Machining distortion law curve

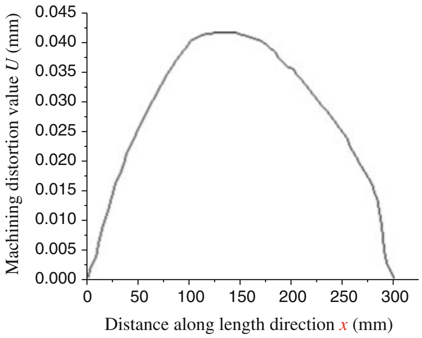


Fig. 10 Machining distortion law curve

to zero to deactivate the element, simultaneously, the quality, damp, and specific heat were all set to zero.

The simulation and analysis schemes were that initial residual stress, cutting loads, and coupling action of these two effect factors were taken into account, respectively, to perform finite element simulations, by comparing the results of three kinds of simulations, finding out the cause and main effect element of machining distortion for titanium alloy aircraft monolithic component.

2.3.1 Effect of initial residual stress

Only considering the effect of initial residual stress on machining distortion, finite element simulation of machining distortion process for titanium alloy aircraft monolithic component was carried out, and the simulation results are shown in Figs. 7 and 8.

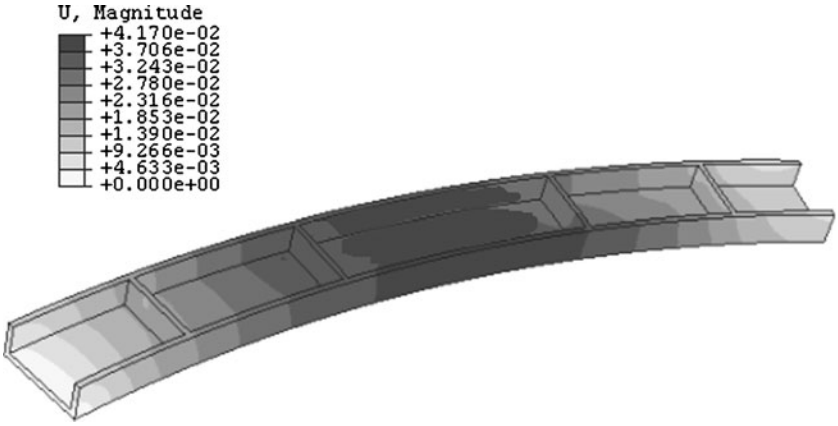
Figure 7 is the distortion plot after machining process simulation, and Fig. 8 is the corresponding machining distortion law curve of machining distortion along length direction for titanium alloy aircraft monolithic component. As can be seen from these graphs, titanium alloy aircraft monolithic component appears convex and bending distortion, with a law of symmetric distribution from the middle to two sides. The maximum distortion position lies in the middle of the component and the maximum distortion value is 0.000186 mm, which shows that the action of initial residual stress only causes very little machining distortion.

2.3.2 Effect of cutting loads

Only considering the effect of cutting loads (including cutting force and temperature) on machining distortion, finite element simulation of machining distortion process for titanium alloy aircraft monolithic component was carried out, and the simulation results are shown in Figs. 9 and 10.

Figure 9 is the distortion plot after machining process simulation, and Fig. 10 is the corresponding machining distortion law curve of machining distortion along the length direction for titanium alloy aircraft monolithic component. It can be seen from these graphs that the convex and bending distortion is also found. The maximum distortion position appears around the middle of component but does not lie in the middle. The distance between the maximum distortion position and machining beginning is 142.147 mm. Simultaneously, the machining distortion presents unsymmetrical distribution, and the slope of distortion curve changes very little on either side of peak, showing the bending distortion around the maximum distortion position is gently. The maximum distortion value is 0.0417 mm, which is bigger than the distortion value only considering the effect of initial residual stress, indicating the

Fig. 9 Simulation result of machining distortion only considering cutting loads



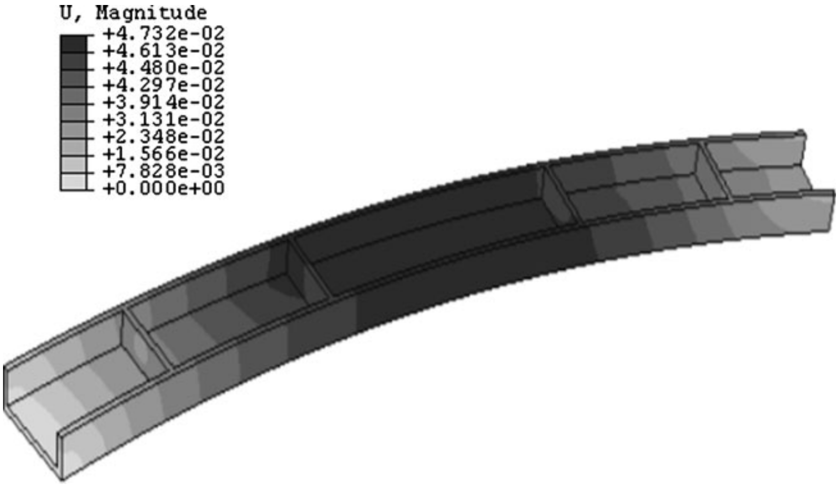


Fig. 11 Simulation result of machining distortion with coupling action

action of cutting loads has great influence on machining distortion.

2.3.3 *Effect of coupling action between initial residual stress and cutting loads*

Taking into account the coupling action of initial residual stress and cutting loads (including cutting force and temperature), finite element simulation of machining distortion process for titanium alloy aircraft monolithic component was carried out, and the simulation results are shown in Figs. 11 and 12.

Figure 11 is the distortion plot after machining process simulation, and Fig. 12 is the corresponding machining distortion law curve of machining distortion along length direction for titanium alloy aircraft monolithic component. As can be seen from these graphs, titanium alloy aircraft monolithic component also appears convex and bending distortion with coupling action of initial residual stress and cutting loads. The maximum distortion position appears around the middle of component, also does not lie in the middle. The distance between the maximum distortion position and machining beginning is 144.783 mm. Simultaneously, the machining distortion also shows unsymmetrical distribution, and the slope of distortion curve changes very little on either side of peak, indicating the bending distortion around the maximum distortion position is also gently. The maximum distortion value is 0.0473 mm, which is larger than the distortion value only considering the effect of initial residual stress, but close to the distortion value only considering the effect of cutting loads, showing the machining distortion law of coupling action is in agreement with law of cutting loads action.

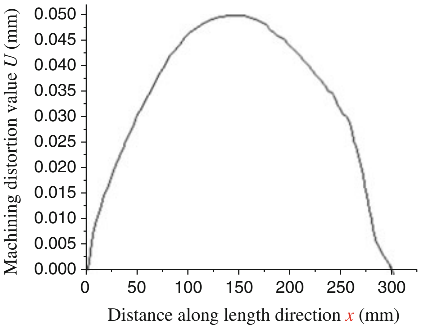


Fig. 12 Machining distortion law curve

2.4 Experiment verification

To verify the finite element simulation results, machining distortion experiment for titanium alloy aircraft monolithic component was performed on an MV-5A CNC machining center. The cutting conditions used in the experiment are listed in Table 4, and the experiment result is shown in Fig. 13.

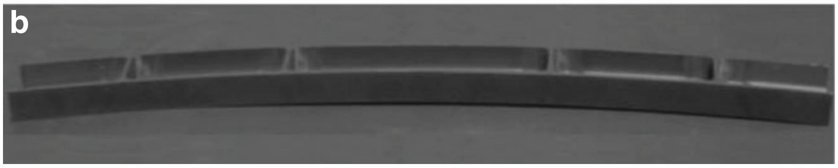
As can be seen from above photos, the machined part appears convex and bending distortion and the maximum distortion position lies around the middle part. A feeler gauge was adopted to measure the distortion dimension of machined part. The distance between the maximum distortion position

Table 4 Cutting conditions

Workpiece material	Titanium alloy Ti6Al4V
Cutting type	End milling
Tool material	Carbide
Tool diameter/mm	φ10
Tool rake angle	22°
Tool cearance angle	8°
Tool inclination angle	30°
Number of tool tooth	2
Axial cutting depth/mm	3
Feeding speed/(mm/min)	128
Radial cutting width/mm	2
Rotation speed/(r/min)	555

Fig. 13 Machining distortion experiment result

Machined part



Machining distortion of part

and machining beginning is 147.7 mm. The maximum simulation distortion value and measurement value are compared and listed in Table 5.

On the other hand, a comparison of distorted part from finite element simulation and experiment was carried out (see Figs. 7, 9, 11, and 13).

Based on the above comparisons, it is shown that the machining distortion results from finite element simulation with coupling action of initial residual stress and cutting loads, such as machining distortion law, the maximum distortion position, and the maximum distortion value, agree well with the experiment results.

According to the above finite element simulation and experiment studies, some conclusions can been drawn that there has been significant divergence between machining distortion law from finite element simulation only considering the effect of initial residual stress and experiment results; moreover, the machining distortion law from finite element simulation considering the effect of cutting loads and coupling action are both in good agreement with experiment results, while machining distortion law of the latter is more close to the real distortion. The results show that cutting loads (including cutting force and temperature) are the main effect element of machining distortion for titanium alloy aircraft monolithic component, which play an important role in machining distortion, while the initial residual stress is less important element, only causing very little machining distortion.

Table 5 Comparison of the maximum simulation and measurement distortion values

Effect factor Distortion value	Action of initial residual stress	Action of cutting loads	Coupling action of two factors
Simulation value *y*/mm	0.000186	0.0417	0.0473
Experiment value *y*/mm	0.056	0.056	0.056
Errors *e*%	99.7	25.5	15.5

Also, the research results show that machining distortion for titanium alloy aircraft monolithic component is the common-effect of kinds of factors. Machining distortion is closely connected with residual stress. The residual stress is produced on the machined surface of workpiece together with elastic–plastic deformation and thermoplastic deformation due to the actions of cutting loads and clamping from machining process, which is named machining-induced stress. When large amount of material is removed, the equilibration of machining-induced stress and initial residual stress is broken, and these two kinds of residual stresses are redistributed to re-equilibrate it, so causing machining distortion for titanium alloy aircraft monolithic component.

3 Conclusions

(1) Machining distortions of aluminum alloy and titanium alloy aircraft monolithic component are studied by finite element simulation and experiment. The prediction accuracy of the finite element simulation is validated experimentally, and the obtained simulation and experiment results are found in good agreement, which proves that it is practicable to investigate machining distortion process by finite element simulation technology.

(2) The research results show that the initial residual stress in the blank is the main effect element of machining distortion for aluminum alloy aircraft monolithic component, while cutting loads (including cutting force and temperature) are the main effect element of machining distortion for titanium alloy aircraft monolithic component.

(3) For titanium alloy aircraft monolithic component, machining distortion is the common-effect of kinds of factors and is closely connected with residual stress. When large amount of material is removed, the

equilibration of machining-induced stress and initial residual stress is broken. To re-equilibrate it, these two kinds of residual stresses are redistributed, and the common action of these two kinds of residual stresses causes machining distortion.

(4) This work makes clear the main root cause of machining distortion for aluminum alloy and titanium alloy aircraft monolithic component. To decrease machining distortion of aluminum alloy aircraft monolithic component, the initial residual stress in the blank must be controlled first. Similarly, to decrease machining distortion of titanium alloy aircraft monolithic component, the cutting loads must be controlled first.

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