Research on Machining Fixture Layout Optimization for Near-Net-Shaped Jet Engine Blade

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Abstract. The design of machining fixture layout optimization for near-net-shaped jet engine blade is a major problem in the blade processing and manufacturing process. In this paper, the mathematical model of machining fixture layout optimization is established, and the influence of the clamping point position on the machining deformation of the blade-fixture system is analysed. Firstly, the mathematical model of machining fixture layout optimization is established according to the process requirements and clamping characteristics. Secondly, the positioning clamp points of machining fixture is optimized by the combination of finite element analysis (FEA) and genetic algorithm under the optimization target of the minimum value of the maximum deformation of the blade. Finally, cutting experiments are carried out to verify the reliability of the optimal layout fixtures, and the feasibility of the algorithm is verified by comparing with the minimum value obtained by the traditional Monte Carlo statistical method.

1. Introduction

The manufacturing of aero-engines precision forging blade is transforming towards to intelligent manufacturing. In the process of precision forging blade, the traditional process is that the low-melting alloy casting process is used as the positioning clamping tool for machining processing, which is not only seriously pollution, but also unable to meet efficiency requirements. Therefore, the clamping scheme of multi-point directly positioning is a good choice for the current blade precision process [1, 2]. Fixture design and optimization will be a major problem.

Many scholars have conducted research on the optimization design of thin-walled clamping fixture. Gene et al. proposed a dynamic model and analysis method for workpiece-fixture system, and analysed the influence of three parameters of fixture size, position and sequence on fixture [3]. HAMEDI et al. studied a nonlinear finite element analysis system combining artificial neural network and genetic algorithm, and analysed the optimal clamping force of fixture [4]. Wang et al. used FEA to optimize the clamping deformation of thin-walled curved parts [5]. Qin established a mathematical model based on the historical dependence of friction caused by friction, solved the influence of clamping force and clamping sequence on deformation by FEM [6]. Zhou et al. used genetic algorithm to optimize the fixture layout and clamping force of fixture [7, 8].

Based on the above analysis, it can be seen that the current research has focused on the optimization of the fixture for the simple aluminum alloy shapes (arc or bottomless). There is no
optimized analysis method for the precision-forged blade fixture of titanium alloy materials. In fact, there are still many problems in the low-melting alloy casting fixture for replacing the precision forging blade. Although the new fixture solves the problems of pollution and processing efficiency, it also reduces the rigidity of the workpiece- fixture system, and introduces large blade deformation during the process.

2. Fixture layout optimization model
In the process of precision forging blade Tenon root, the new fixture mainly adopts multi-point positioning and direct clamping to clamp the blade body. Among them, the precision forged blade is a thin-walled material whose surface is curved, which is titanium alloy (elastic modulus 110GPa), and the clamping element uses PEEK-GF30 (elastic modulus 7GPa).

Figure 1 Positioning clamp point layout of fixture
In actual machining, the blade types are varied and varied, so a new type of fixture is required for each blade. In this paper, a three-stage stator compressor blade is taken as the example, and its containment boundary is 200x100x5mm. The clamping of the new fixture consists of 4 clamping points, 5 positioning points and 4 auxiliary positioning points, as shown in Figure 1. During the processing of the blade Tenon root, the fixture mainly clamps the blade body by four clamping points at the back of the blade. In the selection of the initial four clamping points, the blade body reference point in the blade precision forging coordinate system is empirically selected, but in the actual blade boring process, the position layout of the four clamping points is determined for the blade- fixture system stiffness. Therefore, rationally arranging the position layout of the four clamping points of the new fixture can effectively improve the stiffness of the blade-tooling system, thereby improving the processing quality of the blade Tenon root.

2.1 Model assumptions
To facilitate the final problem solving, make the following assumptions:

(1) During the processing of the blade Tenon root, the rigidity of the system is insufficient. The blade is subjected to the cutting load under the condition of clamping and will be elastically deformed in the longitudinal direction. Therefore, the model can be simplified and simplified into 8 cylinders to clamp the blade.

(2) The contact areas of the four clamping points are the same, and the clamping force is the same.

(3) The blade Tenon root is subjected to a time-varying cutting load during the actual machining process, but the blade deformation is greatest when the load acts on the blade Tenon root. Therefore, it is assumed that a static load is applied at the Tenon root of the blade [9].

2.2 Finite element model
A finite element model is established and solved by genetic algorithm.

(1) Meshing the simplified blade- fixture system. There are 21,700 nodes and 10070 units.

(2) The boundary conditions of the finite element model are:
There are 8 elastically constrained contact faces between the simplified blade and the fixture component, wherein $P_i (i=1\sim4)$ is in contact with the blade as frictional contact, friction coefficient $\mu=0.48$, $Q_j (j=1\sim4)$ Contact with the blade is defined as a binding contact.

Defining $Q_j (j=1\sim4)$, the bottom end of the four cylinders does not produce displacement. The four cylinders at $P_i (i=1\sim4)$ are clamped by 2200N pressure, and the 8 N force acts perpendicularly at the end of the blade Tenon root. Simulate external loads.

(3) Using finite element software to solve the blade deformation.

### 2.3 Mathematical modelling

The blade Tenon root is affected by the time-varying cutting load during the actual machining process. Therefore, the dynamic equation in the classical mechanic’s theory can be used to describe the deformation during the machining process caused by the cutting force, as shown in equation (1).

$$[M]\ddot{d} + [C]\dot{d} + [K]d = \{F(t)\}$$  \hspace{1cm} (1)

In order to facilitate the solution of the model, the dynamic process is transforming into a static process under the assumption of the model. That is, the influence of inertia and damping on the blade- fixture system is not considered, and the stiffness matrix is continuous. Therefore, equation (1) can be converted to linear static structure analysis, as shown in equation (2).

$$[K]d = \{F(t)\}$$  \hspace{1cm} (2)

In order to determine the optimal position of the fixture layout, the layout of each clamping position within the blade containment boundary is optimized (the initial position of the blade clamping point is shown in $P_1$, $P_2$, $P_3$ and $P_4$ in Figure 1(a), which is the precision forging coordinate. The reference point of the blade body under the system. The position of the clamping point is assumed in Table 1,

| Table 1 Blade body clamping point position |
|-------------------------------------------|
| Clamping point  | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
| Position        | $x_1, y_1$ | $x_2, y_2$ | $x_3, y_3$ | $x_4, y_4$ |

The minimum value of the maximum deformation amount of the blade Tenon root is selected as the objective function in all cases, as shown as Equation 3

$$d = \min(\max(|d_1|, |d_2|, ..., |d_k|, ..., |d_n|))$$  \hspace{1cm} (3)

where, $d$ represents the optimal deformation amount, $d_i$ represents the deformation amount of the blade during machining process, and $n$ represents the number of selected samples, and the larger $n$ indicates the closer to the actual working condition.

The position change range of the position point is as shown in Equation 4.

$$24.2mm \leq x_1 \leq 29.7mm, \quad 2.5mm \leq y_1 \leq 3.1mm$$
$$26mm \leq x_2 \leq 31.8mm, \quad 1.3mm \leq y_2 \leq 1.6mm$$
$$21.3mm \leq x_3 \leq 26mm, \quad 103.7mm \leq y_3 \leq 126.7mm$$
$$21.3mm \leq x_4 \leq 26mm, \quad 100.1mm \leq y_4 \leq 122.3mm$$  \hspace{1cm} (4)

The cutting force load is shown in Equation 5.

$$\mu |F_{cl}| \geq \sqrt{F_{xi}^2 + F_{yi}^2} \hspace{1cm} i = 1, 2, 3, 4$$  \hspace{1cm} (5)

$F_{cl}$ is the clamping force required for to clamping force, $F_{xi}$, $F_{yi}$ are the tangential force between the clamping element and the blade body, and $\mu$ is the friction factor.
2.4 Model solving

The genetic algorithm is simply a randomized search method that simulates the survival of the fittest and the survival of the fittest. The genetic algorithm is used to determine the clamping component layout of the blade fixture. The position of the clamping component needs to be randomly reorganized within the containment boundary, and combined with the finite element method to solve multiple sets of solutions, and finally the best blade fixture layout is obtained. Solve the flow chart of the optimal layout scheme of the blade tooling, as shown in Figure 2.

In traditional genetic algorithms, the choice of roulette is used to select the appropriate chromosome. However, the operator's ability to select is not high, and it is prone to premature convergence. Pareto proposed the concept of Pareto Optimal in 1896, and now ANSYS replaces the choice of roulette with the Pareto advantage. When goals and constraints conflict with each other and there is no ideal group, the Pareto advantage provides a set of solutions. Always sacrifice at least one target or constraint group while improving at least one other target or constraint. This paper uses the Pareto advantage to solve the model.

3. Experimental verification

Table 2 shows the best position and the fixture layout obtained by combining the genetic algorithm and the finite element solution. Figure 3 shows the convergence trend of the optimization algorithm.

Table 2 The optimized clamping point position

| Parameter | Candidate point 1 | Candidate point 2 | Candidate point 3 |
|-----------|------------------|------------------|------------------|
| X_1       | 29.634           | 29.583           | 29.582           |
| Y_1       | 2.6693           | 2.7404           | 2.7402           |
| X_2       | 31.174           | 31.092           | 30.829           |
| Y_2       | 1.4384           | 1.3685           | 1.5778           |
| X_3       | 21.84            | 21.625           | 21.994           |
| Y_3       | 110.79           | 105.31           | 104.46           |
| X_4       | 22.643           | 21.362           | 21.949           |
| Y_4       | 115.35           | 101              | 110.75           |
| Deformation | 0.10438         | 0.10618          | 0.10646          |
In order to verify that the optimized fixture has good dynamic behavior, the cutting experiment analysis of the fixture is performed. Figure 4 shows the fixture structure at different positioning positions. Four sets of typical positions are taken for the cutting dynamics comparison experiment. Fixture C is designed according to the optimized positioning point.

The experimental site is shown in Figure 5. The laser displacement sensor is used to measure the dynamic response signal of the fixture during the cutting process. Under the same cutting process parameters, the same cutting force is obtained. By comparing the changes of the displacement response, the fixture stiffness is analysed.

Figure 6 shows the change of the displacement response signal during the cutting process. Comparing the four fixtures, it can be analyzed that the displacement response of the fixture C is the smallest, so the stiffness of fixture C is significantly better than other fixtures. This also shows that the proposed fixture optimization design analysis method is reliable.

4. Conclusion
In this work, the design of machining fixture layout optimization is analysed by mathematical model, FEA and genetic algorithm. It is verified by experiments that the obtained optimal fixture is reliable, the rigidity of the fixture is obviously improved, and the proposed analysis method is reliable.

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