

Contact stress analysis and optimization of single crystal turbine blade tenon/disk mortise structure considering thermal-solid coupling

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Abstract. Contact stress analysis and optimization design of single crystal turbine blade tenon/disk mortise structure considering thermal-solid coupling is proposed in this paper. Contact thermal conductivity analysis of turbine blade/disk mortise structure is carried out to obtain temperature distribution. Contact stress of mortise structure considering temperature influence is analyzed by FEM method. On basis of contact stress analysis, the optimization design method considering thermal-solid coupling is proposed. Broaching angle, wedge angle and gap distance are chosen as optimization design variables. The minimum Mises stress, average tensile stress and average compressive stress are chosen as optimization objectives. A three fir tree tenon/mortise structure is optimized to decrease the maximum Mises stress 14% by proposed method.

1 Introduction

The single crystal (SC) alloy has been widely applied for aircraft engine high pressure turbine blades, due to its fatigue and creep characteristics in high temperature. SC turbine blade always connect powder metallurgy (PM) disk with fir tree tenon/mortise structure. The blade tenon/disk mortise structure works at about 700 °C environment. High temperature working environment would reduce material properties of tenon/mortise structure. Meanwhile, blade tenon/disk mortise structure thermal deformations can cause contact load assign among blade tenon. So, analysis and design of SC turbine blade/PM disc fir tree tenon/mortise structure should consider thermal-solid coupling. Because contact stress is sensitive to size of tenon/ mortise structure, so it is important to optimize tenon/mortise structure to obtain minimum contact stress.

Cui[1] used finite element method to analyze contact stress of a coattail-type tenon/mortise structure at room temperature. Wang[2] studied the effect of processing tolerance on contact by finite element analysis. Wang[3] investigated effects of contact gap on contact properties of turbine blade tenon /mortise. Liao[4] introduced a collaborative optimization strategy to optimize a typical fir-tree mortise structure. Shen[5] optimized a three pairs of teeth fir-tree tenon/mortise structure and decreased the maximum equivalent stress by 12%. Yang[6] employed multi-island genetic algorithm and sequential quadratic programming to optimize turbine tenon/mortise. It can be seen from current literatures that most analysis and design of tenon/mortise structure do not considering effects of temperature.

This paper aims to propose a SC blade tenon/PM disk mortise structure optimization method considering thermal-solid coupling. The main works include two sections. Firstly, the contact stress analysis considering thermal-solid coupling is carried out. Secondly, optimization of blade tenon/ disc mortise structure is studied. Finally, a SC blade tenon/PM disk mortise structure is optimized by method proposed

2 Contact analysis of SC blade tenon/PM disk mortise structure considering thermal-solid coupling

The tenon/mortise structure which connected single crystal turbine blade and powder metallurgy disk is shown in Fig.1. The centrifugal load blade suffered is transferred to disk through contact surface of tenon/mortise structure. Because SC turbine blade tenon/PM disk mortise structure works at a high temperature about 700 °C, so the contact analysis considering temperature is necessary. In this work, the contact thermal analysis and contact stress analysis are carried out sequentially.

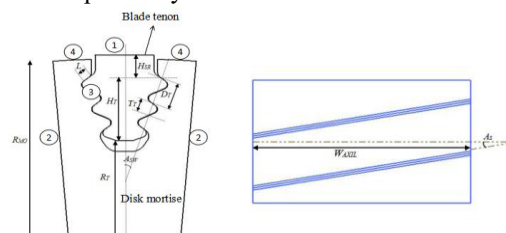


Figure 1. Schematic of a three pairs of teeth tenon/mortise structure

2.1 Contact thermal analysis

Turbine blade work around the high temperature combustion gas. Heat will transfer from blade to disk through contact surface. Relative low temperature air is used to reduce working temperature which flows through gaps between tenon and mortise. In this paper, the contact thermal analysis is carried out by FEM method. Thermal conductivity and specific heat capacity of blade material CMSX-2 and disk material Rene95 are shown in Table 1-4.

Table 1. Thermal conductivity at different temperature of CMSX-2

Temperature/°C	300	500	700	900	1000	1100
Thermal conductivity ($W / (m \cdot ^\circ C)$)	13.9	20.2	24.6	30.0	33.2	10.2

Table 2. Specific heat capacity at different temperature of CMSX-2

Temperature/°C	300	500	700	900	1000	1100
Specific heat capacity ($J / (kg \cdot ^\circ C)$)	490	507	557	662	733	821

Table 3. Thermal conductivity at different temperature of Rene95

Temperature/°C	200	300	500	700	900	1000
Thermal conductivity ($W / (m \cdot ^\circ C)$)	10.5	11.7	13.9	15.7	18.4	20.0

Table 4. Specific heat capacity at different temperature of Rene95

Temperature/°C	200	300	400	500	600
Specific heat capacity ($J / (kg \cdot ^\circ C)$)	443.4	447.4	453.2	458.9	516.7

The SC blade tenon/ PM disk mortise structure is divided to mesh grids for contact thermal analysis. Thermal contact coefficient $TCC = 3000$ is applied on contact surface. Convective heat transfer coefficient $60W / m^2 \cdot K$ is applied for heat exchange analysis when cooling air flows through gaps between tenon and mortise. The first thermal boundary condition $800^\circ C$ is applied on the top surface of blade tenon. In this paper, The FEM software Ansys is employed to contact thermal analysis. Fig.2-3 give the temperature distribution of blade and disk after contact thermal analysis. It can be shown that the top surface of blade tenon has the highest temperature. The maximum temperature of disk is about $750^\circ C$, which located at region of mortise. The structure temperature decreases as radius decreases.

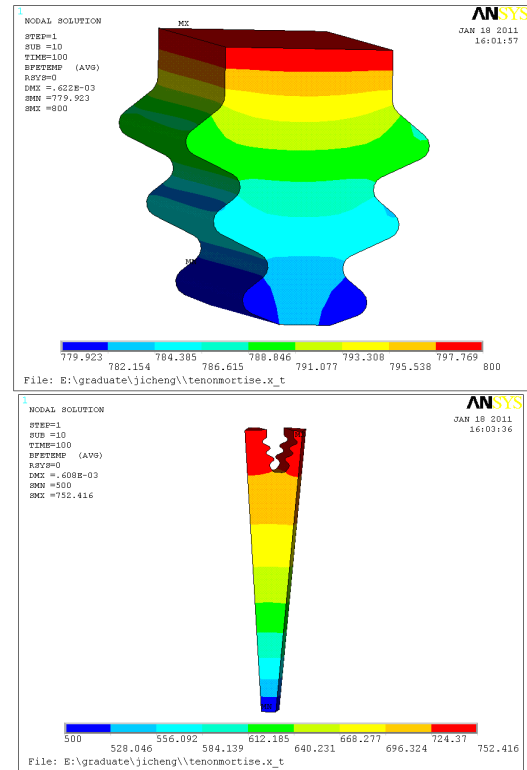


Figure 2. Temperature distribution of blade and disk after contact thermal analysis

2.2 Contact stress analysis of SC blade tenon/PM disk mortise

Nickel-base single crystal alloy having face centered cubic is a classical anisotropy material. The elastic stress strain relationship of single crystal alloy can be expressed by following Eq.

$$\sigma' = C \varepsilon'$$

where, σ is stress vector, and $\sigma' = \{\sigma_{11}, \sigma_{22}, \sigma_{33}, \tau_{12}, \tau_{13}, \tau_{23}\}$. ε is strain vector and $\varepsilon' = \{\varepsilon_{11}, \varepsilon_{22}, \varepsilon_{33}, \gamma_{12}, \gamma_{13}, \gamma_{23}\}$.

The matrix C can be expressed as

$$[C] = \begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix}$$

where, C_{11}, C_{12}, C_{44} is a function of elastic modulus E , Poisson ration ν and shear modulus G .

$$C_{11} = \frac{2(1-\nu)E}{(1+\nu)(1-2\nu)}$$

$$C_{12} = \frac{2\nu E}{(1+\nu)(1-2\nu)}$$

$$C_{44} = G$$

The material constants of CMSX2 along <001> crystallographic orientation is shown in Table 5. The material constants of disk material Rene95 is shown in Table 6.

Table 5. The material constants of CMSX2 along <001> crystallographic orientation

Temperature(°C)	E (GPa)	ν	G (GPa)
20	115	0.313	137
700	89	0.322	113
800	85	0.326	107
850	78	0.330	104

Table 6. The material constants of disk material Rene95

Temperature(°C)	E (GPa)	ν
20	211	0.288
350	188.5	0.192
400	187.5	0.189
450	184	0.183
500	179	0.175
550	174.5	0.168
650	169	0.167

FEM software Ansys is employed to analyze contact stress of single crystal turbine blade tenon/power disk mortise structure. Periodic boundary conditions are applied on the surface besides disk mortise in order to simulate the entire turbine disk. A equivalent pressure load $p = 255.2MPa$ conversd by blade centrifugal load is applied on the top surface of blade tenon. Because contact stress has large gradient and sensitive to mesh grids on contact surface, so grids on contact surface is meshed very small. And the meshed grid is checked by grid-independent test in order to analyze accurately.

Fig.3 gives the Mises stress distribution of SC blade tenon. It can be seen that the maximum contact stresses locate at the boundary regions of contact surface. In the three pairs of turbine blade tooth, the third pairs of tooth have the maximum Mises stress 809MPa. The contact stresses of first and second pairs of tooth are lower than the third pairs of tooth. The first pairs of tooth maximum stress is 493MPa, the second pairs of tooth maximum stress is 624MPa.

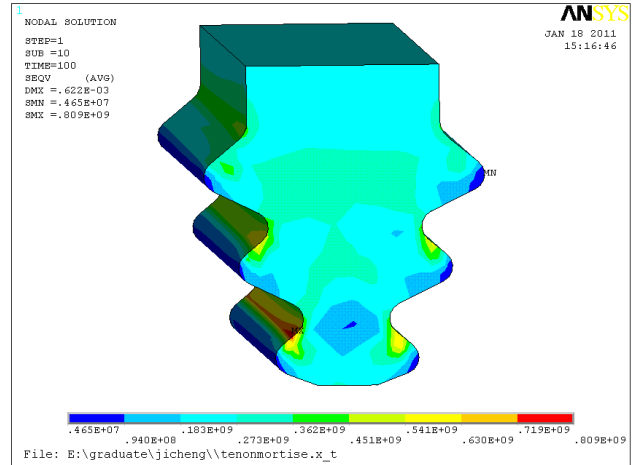


Figure 3. Mises stress distribution of single crystal blade tenon

Fig.4 gives the Mises stress distribution of PM disk mortise. It can be seen that the maximum contact stresses also locate at the boundary regions of contact surface. The first, second and third pairs of tooth maximum Mises stress are 622MPa, 711MPa and 711MPa.

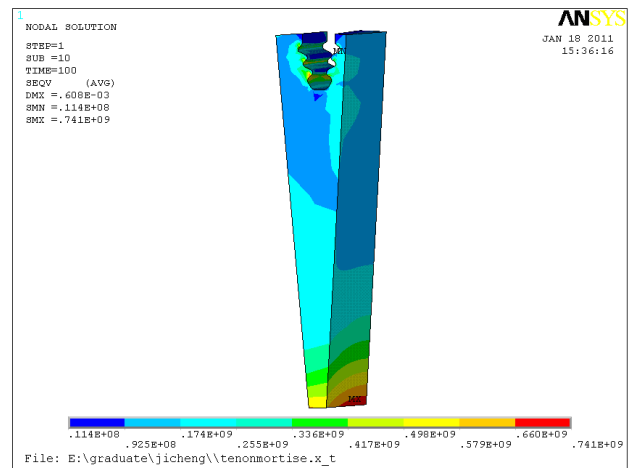


Figure 4. Mises stress distribution of disk mortise

3 Optimization

Optimization of SC blade tenon/PM disk mortise structure to reduce structural stress is carried out on basis of contact thermal and stress analysis. Fig.5 gives the optimization flowchart of single crystal blade tenon/disk mortise structure optimization. Firstly, the parameterized blade tenon/disk mortise structure is created. Then, the automated contact thermal analysis and contact stress analysis are carried out orderly. Optimization algorithm is used to optimize turbine tenon/mortise.

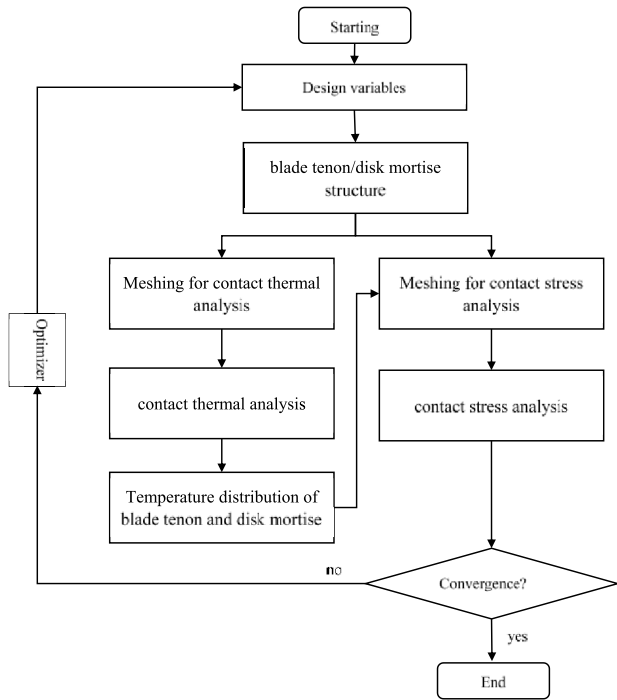


Figure 5. Flowchart of SC blade tenon/PM disk mortise structure optimization

The parametric tenon/mortise structure is shown in Fig.1. There are several design variables for tenon/mortise structure, such as contact line L , tooth distance D_t , broaching angles A_s , wedge angles A_{sw} , gap distance G_t and so on. The broaching angles A_s , wedge angles A_{sw} , gap distance G_t and tooth distance D_t are chosen as optimization design variables which impact contact stress significantly. Blade tenon/disk mortise structure could occur extrusion damage and tensile failure. So the minimum Mises stress, average tensile stress of tenon and mortise, average compressive stress of teeth are chosen as optimal objectives. The optimization of single crystal blade tenon/disk mortise structure can be formulated as following.

$$\left\{ \begin{array}{l} \text{find} \quad A_s, A_{sw}, G_t, D_t \\ \text{min} \quad f = F(\sigma_t, \sigma_m, \sigma_{TA}, \sigma_{MA}, \sigma_{TC}) \\ \quad A_s^l \leq A_s \leq A_s^u \\ \quad A_{sw}^l \leq A_{sw} \leq A_{sw}^u \\ \text{s.t.} \quad G_t^l \leq G_t \leq G_t^u \\ \quad D_t^l \leq D_t \leq D_t^u \\ \quad \sigma \leq [\sigma] \end{array} \right.$$

Where, $F(\sigma_t, \sigma_m, \sigma_{TA}, \sigma_{MA}, \sigma_{TC})$ is multi-objective function of stress σ . σ_t is the maximum Mises stress of single crystal blade tenon. σ_m is the maximum Mises stress of disk. σ_{TA} and σ_{MA} are average tensile stress of

tenon and mortise. σ_{TC} is the average compressive stress of blade tenon tooth. $[\]$ means allowable values. $i = 1, \dots, 5$ mean gap between tenon and mortise of each teeth.

In this paper, Multi-island genetic algorithm is used to optimize turbine tenon/mortise. After optimization, the maximum Mises stress of SC blade tenon is decrease 14% relatively. The maximum Mises stress of disk mortise is decrease 3.2% relatively.

Table 7. Comparison of objectives between original and optimized

	constraint	objectives	original	optimized
σ_t /MPa	860	↓	808.5	692.1
σ_m /MPa	1095	↓	741.3	717.2
σ_{TA} /MPa	344	↓	243.5	242.4
σ_{MA} /MPa	438	↓	174.5	182.4
σ_{TC} /MPa	473	↓	500.8	456.3

Table 8. Comparison of design variables between original and optimized

Design variable	Low limit	Up limit	original	optimized
A_s /°	0	14	9	3.81
A_{sw} /°	12.5	20	19.76	13.42
G_{T1} /°	0.007	0.02	0.007	0.015
G_{T2} /°	0.01	0.05	0.04	0.033
G_{T3} /°	0.01	0.03	0.01	0.025
G_{T4} /°	0.01	0.05	0.04	0.022
G_{T5} /°	0.01	0.03	0.02	0.012
D_t /°	2.6	2.7	2.67	2.7

4 Conclusion

The blade tenon/disk mortise structure suffers centrifugal and thermal load at the same time. So, the contact analysis considering thermal-solid coupling is necessary. An optimization method which analyzing contact thermal and contact stress sequentially is introduced in this paper. A three fir tree SC blade tenon/PM mortise structure is optimized to decrease the maximum Mises stress 14% by proposed method

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