Thermomechanical Fatigue Life Prediction Method of the Trailing Edge Holes in the Turbine Blade for Turboshaft Engine

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Abstract. In this paper, a thermomechanical fatigue (TMF) life analysis method considering stress relaxation was established for turbine blade in a turboshaft engine. The nonlinear creep deformation of a superalloy is predicted by coupling creep damage in the framework of viscoplastic theory. The results revealed that the calculation error of the model for the elastic-plastic stress-strain curve was less than 5%, while the simulation accuracy for the creep curve is within the dispersion range of the inherent properties of material creep deformation. Based on the elastic-plastic creep analysis of a turbine blade, the creep damage and its evolution law of the leading edge and trailing edge of the blade are clarified, and a new method is provided for determining the local dangerous points on the blade. With the help of the linear damage cumulative life theory, the fatigue creep life of the trailing edge hole of a turbine blade considering the stress relaxation is obtained, which provides a more reasonable and better engineering application method for the blade life evaluation.

Keywords. Thermomechanical fatigue; creep; life prediction; gas turbine blade; damage.

1. Introduction
The turbine blade is among the most important of components in the aeroengine, its long-term stable service has an important influence on the economy and safety of engine overhaul. Single-crystal superalloys have been widely used in hot-end components of advanced aero engines because of their high temperature resistance, creep resistance, thermo-mechanical fatigue properties, and good microstructure stability [1]. Turbine blades are typical aero-engine hot-end components. In order to improve the service temperature of turbine blades, film cooling holes (FCHs) are used on the surface of the blades to enable the material to sustain the high temperatures. The dense FCHs destroy the overall structural integrity of the blade, resulting in the concentration of stress at the edge of the hole. Under the high temperature and local stress, film cooling holes (FCHs) at the trailing edge becomes a dangerous point because of the increase of nominal stress caused by the reduction of local bearing cross section and local stress concentration caused by the hole characteristics. With the improvement of gas turbine performance, the temperature bearing capacity of these local dangerous points on gas turbine blades has been in the limit value of strength design, it is urgent to transfer the traditional linear elastic analysis to the precise analysis of nonlinear behavior under complex loads, and it must be considering the multi-damage coupling effect caused by fatigue and creep in the life analysis.

High-precision and high-efficiency numerical simulation of creep-fatigue deformation in a wide temperature and stress range is the precondition of life evaluation, and creep-fatigue is a typical nonlinear load at high temperature. The creep-fatigue behavior of various materials has been
previously studied, include but not limited to stress relaxation, crack initiation, damage constitutive relationship and life prediction methods [2-6]. Wen et al. [7] considering the effect of the multiaxial stress state caused by FCHs on the creep behavior of Ni-based single-crystal superalloy. The results show that the creep life of specimens with multi-holes was significantly decrease due to the multi-hole interference effect. In order to predict the creep life with holes, the modified skeletal point stress method (SPSM) was used. The finite element calculation results and the test results are within twice dispersion zone.

At present, in order to predict the life of turbine blades, in most cases, the steady-state stress-temperature combination is used to clarify the use time of the blades in each state, and the creep-fatigue life of the blades is calculated based on the linear accumulation of fatigue damage and creep damage. Among them, the fatigue damage model has many forms according to the considered force state and load characteristics, while the creep damage is mostly directly used by the Larson-Miller model [8-10]. Due to the large difference in creep deformation rate at different stages, there is an error in mathematical description by using the linear damage accumulation method, and the development of creep damage calculation method can reflect the actual structure after stress relaxation and can provide a more accurate way for life prediction.

In the first section of this paper, the material and finite element model are introduced. The second section shows the crystallographic constitutive relationship used for finite element simulations. Finally, the numerical prediction is presented and discussed.

2. Materials and Finite Element Model

In this study, the gas turbine blade was processed from a polycrystalline superalloy. On the basis of the hexahedral mesh generation method, the turbine blade finite element model was achieved of 35436 nodes and 31516 elements, as shown in figure 1.

![Figure 1. Finite Element model of the turbine blade.](image)

The calculation conditions of blade were specially designed to simulate the actual service environment of turbine blades and investigate the effects of the film cooling hole structure on the mechanical properties of material. The blade load cycle was set by service engine speed spectrum. The rotational speed profile for finite element calculation is shown in figures 2a-2b, where “horizontal line” is the dwell time with hold normalized rotational speed and the time speeds 400s per cycle. The blade temperature field was obtained by aerodynamic analysis. The temperature field in turbine blade at different time was loaded on finite element model by interpolation and heat transfer calculation. In
order to limit the rigid body displacement of the blade, the normal displacement constraint of fir-tree tooth was zero, and the axial displacement constraint of the front face was zero.

![Figure 2. Rotational speed profile for finite element calculation (a) Cyclic load spectrum (b) Creep load spectrum.](image)

3. Constitutive Modeling and Material Parameters

The total strain rate tensor is divided into the elastic and inelastic strain rate components, expressed as:

$$
\varepsilon_{ij}^e = \varepsilon_{ij} + \varepsilon_{ij}^m
$$

(1)

where $\varepsilon_{ij}$, $\varepsilon_{ij}^e$ and $\varepsilon_{ij}^m$ represent the total, elastic and inelastic strain, respectively. To model the viscoplastic behavior, the elastic strain is defined by Hooke relationship:

$$
\varepsilon_{ij}^m = C_{ijkl} \sigma_{kl}
$$

(2)

where $\sigma$ represents stress tensor, $C$ represents elastic tensor, expressed as:

$$
[C] = \begin{bmatrix}
1/E & -\mu/E & -\mu/E & 0 & 0 & 0 \\
-\mu/E & 1/E & -\mu/E & 0 & 0 & 0 \\
-\mu/E & -\mu/E & 1/E & 0 & 0 & 0 \\
0 & 0 & 0 & 1/G & 0 & 0 \\
0 & 0 & 0 & 0 & 1/G & 0 \\
0 & 0 & 0 & 0 & 0 & 1/G \\
\end{bmatrix}
$$

(3)

where $E$, $G$ and $\mu$ represent elastic modulus, shear modulus and Poisson’s ratio, respectively.

According to the principle of strain equivalence, the strain constitutive equation for nondestructive materials can be applied to the damaged materials, but the normal stress must be replaced by equivalent stress. Equivalent stress is defined as:

$$
\sigma_{ai} = \sqrt{\frac{1}{2}(\sigma^e - X)^T(\sigma^e - X)}
$$

(4)

where the upper index represents partial tensor, $X$ represents back stress.

Herein, considering creep damage, the equivalent stress can be written as:
\[ \sigma_{eq} = \frac{\sigma_{eq}}{1 - D_c} \]  

(5)

Moreover, a viscoplastic potential developed by Chaboche is summarized as [11]:

\[ \dot{\varepsilon}^i = \frac{3}{2} \left[ \frac{f}{K} \right]^n \left( \frac{\sigma - X_d}{\sigma_m} \right) \frac{1}{1 - D_c} \]  

(6)

where \( \dot{\varepsilon}^i \) is inelastic strain ratio, \( \sigma \) is the deviation of equivalent stress, \( K \) and \( n \) are material parameters, \( f \) is yield function, expressed as:

\[ f = \sigma - R - k \]  

(7)

where \( R \) represents isotropic hardening scalar, \( k \) represents initial yield strength. The evolution equation of back stress is defined as:

\[ \dot{X}_y = c \dot{\varepsilon}^i - a \dot{\varepsilon}^i - \beta J \dot{X}X \]  

(8)

where \( c, a, \beta, r \) are material parameters, \( \dot{\varepsilon}^i \) is equivalent plastic strain ratio. The evolution equation of isotropic hardening scalar is defined as:

\[ \dot{R} = b(W - R) \dot{\varepsilon}^i \]  

(9)

where \( b \) and \( W \) are material parameters. Equivalent plastic strain ratio expressed as:

\[ \dot{\varepsilon}^i = \sqrt{\frac{2}{3}} \varepsilon \dot{\varepsilon}^i \]  

(10)

In order to describe the creep deformation process, the damage evolution equation is [12]:

\[ \dot{D}_c = D_t \left( \frac{\sigma_m - k}{K} \right)^n \frac{1}{(1 - D_c)^n} \]  

(11)

where \( k_0 \) is material parameter, \( D_0, K_d, n_d, k_d \) represent content of damage evolution.

The constitutive parameters at different temperatures were obtained by linear interpolation when calculating the stress and strain of the structure with temperature field. The material parameters were identified from the uniaxial tensile and creep curves through the optimization analysis of Matlab. Furthermore, the Umat subroutine was programmed with Fortran. The results calculated by ABAQUS were compared with tested data to verify the accuracy of the model. Figure 3 shows the stress-strain response of CMSX-4 under monotonic tension using ABAQUS software. A comparison of the tested and calculated uniaxial tensile curves at 20°C, 550°C, 700°C, 760°C, 800°C and 850°C was shown in figure 3. It can be seen that all the curves meet test data of the material and strictly satisfied elastic law. The calculation error of the curves was less than 5%. Figure 4 is FEM calculation of the creep deformation of the superalloy under certain test conditions. The creep curves at 700°C and 800°C were shown in figures 4a and 4b, respectively. The results indicated that all the calculations were high accuracy and were generally within the acceptable dispersion range of the creep test.
Figure 3. Monotonic stress and strain curve simulation at different temperatures for a superalloy (a) 850°C (b) 950°C.

Figure 4. Creep deformation simulation at 850°C and 950°C for a superalloy (a) 700°C (b) 800°C.

4. Results and Discussion

4.1. Stress-Strain Analysis of Turbine Blade

In order to analyze the fatigue and creep damage of turbine blades, the stress and strain under cyclic creep loads were calculated by ABAQUS respectively. The FEM blade model boundary condition was explained in figure 2.

Figure 5 shows the creep damage distribution pattern under load spectrum in figure 2. The result shows that the middle part of the leading and trailing edge of blade are the regions with more serious local creep damage, mainly due to the relatively higher temperature and stress in the region. Further detailed analysis shows that after 405 hours, the creep damage around the hole reaches 0.14 and the creep damage in the surrounding area generally reaches 0.09, which is the most likely place for the local creep-fatigue failure of the blade. Therefore, this study only concentrates on the holes of trailing edge. The result indicates that the area with maximum creep damage locates at hole-11 at trailing edge, as shown in figure 5, and the dangerous point node number was 8405.
Figure 5. Creep damage in the blade and the local creep damage in the eleventh hole at trailing edge.

In order to eliminate the influence of recoverable strain such as elasticity and thermal expansion, the stress and strain data of hole-11 (Node Number: 8405) were extracted, and the main strain creep data were separated, as shown in figure 6. It can be seen that the creep strain first increases rapidly with time and then stabilize. After 100 hours, 200 hours, 300 hours, 400 hours of creep, the creep component of the principal strain was 0.314%, 0.376%, 0.421%, 0.459% respectively, and the maximum principal stress decreased from 338.7 MPa to 202.1 MPa, 185.4 MPa, 174.0 MPa, 164.8 MPa. Therefore, the maximum principal stress also undergoes the fast relaxation transition to the stable relaxation stage.

Figure 6. Maximum principle creep strain and maximum principle stress evolution role at 8405 node in the eleventh hole (a) maximum principal strain of creep (b) maximum principal stress.

Figure 7 is the mechanical principal strain ($\Delta \varepsilon_{\text{m}}$) at node 8405 at hole-11. As it indicates that the stress relaxation is found at the initial idle status due to the local high stress, and the stress redistribution also occurs after the maximum-speed to idle. After cyclic loading, the mechanical strain range of the node varied.
4.2. Thermomechanical Fatigue Life Prediction in the Trailing Edge Hole

The fatigue creep life of Turbine Blade is calculated by linear damage accumulation method. The total damage \( D_t \) is expressed as the sum of fatigue damage \( D_f \) and creep damage \( D_c \), expressed as:

\[
D_t = D_f + D_c
\]  
(12)

where fatigue damage \( D_f \) is obtained based on the liner accumulation of the cycle life \( N_f \), expressed as:

\[
D_f = 1/N_f
\]  
(13)

The fatigue life is based on the classical strain-life model:

\[
\Delta \varepsilon_m = m (N_f)^n
\]  
(14)

where \( \Delta \varepsilon_m \) represents strain range, \( m \) and \( n \) are material parameters. For the superalloy, \( m \) and \( n \) are 0.04073 and -0.1307 respectively. The strain range of 0.342% is plugged into the equation (14) and the fatigue life is 170505788 cycles. Therefore, the fatigue damage \( D_f \) per cycle is 5.86E-9.

In order to calculate the creep damage, the classical Larson-Miller model is used. By fitting the original creep test data, the quantitative relation between material stress and Larson-Miller parameters is obtained, expressed as:

\[
\lg \sigma = -0.30006 + 0.34657 \times P - 0.00922 \times P^2
\]  
(15)

where \( P = (T + 273.15)(20 + \lg t)/1000 \), the unit of \( T \) is degree centigrade, \( t \) is creep rupture time. The creep rupture time can be obtained through the combination of stress and temperature, and the creep damage under a certain holding time can be calculated as \( dt \times (T, \sigma) \). The creep damage is calculated in the whole calculation time by dividing the whole loading time, it defined as:

\[
\Delta \varepsilon_m = 0.00298
\]
\[ D_c = \sum_{i=1}^{n} t_{i} \left( T_i, \sigma_i \right) \Delta t \]  \hspace{1cm} (16)

Using the stress data in figure 6 and the temperature at the node on the blade (839°C), the maximum rotational speed state creep life of node 6768 is calculated to be 322.7 hours. If the cycle time is 40 minutes, the ratio of maximum rotational speed state is 2.7%, and the creep damage is 1.41E-4. According to the damage accumulating model, the total damage is 5.5779E-5, and the thermomechanical fatigue life is 17926 cycles.

5. Conclusion Thermomechanical

A fatigue life analysis method for local structures of turbine blades is presented in this paper. Based on the elastoplastic-creep constitutive model of superalloy, an important tool for analysing the cyclic and creep deformation of turbine blades is obtained, thus, it provides a more practical data input for creep damage calculation. The conclusions are drawn as follows:

- The creep damage is mainly concentrated in the middle part of the blade, especially in the high temperature region of leading edge and trailing edge;
- Based on viscoplastic model, it can provide high precision model guarantee for nonlinear stress-strain analysis of blade. The calculation error of the model is less than 5% for the elastoplastic stress-strain curve, and the simulation accuracy for the creep curve is within the dispersion range of the typical creep test curve;
- Based on the high-precision stress-strain calculation method, it provides more reasonable data input for blade life prediction and an important method for engineering application.

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