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ARTICLE

Numerical Simulation on the Creep Damage Evolution of Nickel-Based Single Crystal Specimens with Slant-Angled Film Cooling Holes

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Abstract: Numerical calculations have been performed to study the creep damage evolution of nickel-based single crystal specimens with slant-angled film cooling holes. The emphasis is the effect of different slant angles on creep properties. The slant angles are 0°, 15°, 30° and 45°. The results show that the distributions of the resolved shear stress around film holes are different under different slant angles. The directions of crack propagation are θ=±54° when α=0°, 15°, 30°; however when α=45° the crack propagation directions are along θ=±46°. The specimen with α=30° has the longest failure life. In the higher stress region near the cooling hole, the phenomenon of stress relaxation will appear, such as resolved shear stress, Mises equivalent stress and stress σ_{11}. And with the time increasing, they reach stable values. Different specimens have different damage distributions. The maximum damage points appear at locations 0°, 0°, 13° and 26° from horizontal direction when the slant angles are 0°, 15°, 30° and 45°, respectively. And thickness has influence on the distribution of resolved shear stress along the holes.

Key words: single crystal superalloy; cooling hole; slant angle; creep damage

Single crystal nickel-based superalloys have been widely used for high temperature applications, such as cooled turbine blades, due to their good creep resistance[1,2]. The studies of their basic creep properties have been extensively carried out[3,4]. In order to achieve a high firing temperature and a high-efficiency of gas turbine engines, a film cooling technology is introduced, which uses cooling holes to reduce the incident convective heat flux on the surface[5]. However, the film cooling holes also destroy the structure integrity of the blades, causing high multi-axial stress state in the region near the cooling holes which becomes the key region of crack initiation. Furthermore, some film cooling holes are not perpendicular to the blade surfaces because of complex geometry shape. The slant angle plays an important role in the strength and the life of blades[6]. Therefore, it is very important to study the stress distributions, lives, strain development characteristics and creep damages with different slant angles.

It was reported that many cooling blades were broken in film cooling holes[7,8]. And the creep deformation and creep damage are the most important factors leading to failure. Some studies on the cooling efficiency and the flow-field characteristics with different shapes and under different arrangements of film cooling holes have been performed so far[9-11]. Kim et al[12] concluded that the laidback hole provided better film cooling performance than other holes. Hou[13], Yu[14] analyzed the elastic-plastic behaviors of nickel-based single crystal with single round hole and obtained the activation mechanism of the slip systems around the hole. Thole[15] compared cooling characteristics of three different holes geometries. Gao[16] listed four common kinds of film-cooling hole configurations and investigated film cooling effectiveness along the axis and with a compound angle. Lu[17] presented five arrangements of cooling holes and introduced the influence of the shape on different arrangements. However, the influence of slant angle on creep properties of film cooling

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hole has been rarely studied.

In the present paper, based on the crystal plasticity theory, the creep properties of Ni-based single crystal alloy plate specimens with different slant-angled cooling holes were studied, including stress distribution, failure life, strain development and creep damage. The results could provide a reference for mechanical properties study of air-cooling blade and future application and design.

1 Creep Prediction Model

For nickel-based single crystal, the resolved shear stress $\tau^{(\alpha)}$ of slip system α can be calculated by

$$\tau^{(\alpha)} = \boldsymbol{P}^{(\alpha)} : \boldsymbol{\sigma} \quad (1)$$

where, $\boldsymbol{\sigma}$ is stress tensor, and $\boldsymbol{P}^{(\alpha)}$ is Schmidt tensor factor, given by

$$\boldsymbol{P}^{(\alpha)} = \frac{1}{2}\left(\boldsymbol{m}^{(\alpha)}\boldsymbol{n}^{(\alpha)^T} + \boldsymbol{n}^{(\alpha)}\boldsymbol{m}^{(\alpha)^T}\right) \quad (2)$$

where, $n^{(\alpha)}$ and $m^{(\alpha)}$ are the unit vectors normal to the slip plane and along the slip direction of the slip system α, respectively.

The total strain rate $\dot{\varepsilon}$ is the summation of the elastic strain rate $\dot{\varepsilon}_e$ and non-elasticity strain rate $\dot{\varepsilon}_c$ (creep strain rate), expressed as follows:

$$\dot{\varepsilon} = \dot{\varepsilon}_e + \dot{\varepsilon}_c \quad (3)$$

Elastic strain rate $\dot{\varepsilon}_e$ can be got by the equation (1). The creep strain rate $\dot{\varepsilon}_c$ related to the resolved shear strain rate is as follows:

$$\dot{\varepsilon}_c = \sum_{\alpha=1}^{N} \dot{\gamma}^{(\alpha)} \boldsymbol{P}^{(\alpha)} \quad (4)$$

Researches have showed that the creep damage mechanism of nickel based single crystal alloy can be grouped into two categories. One is cavitation controlled damage, initiating at the cast fault, and the other is degradation damage[18] caused by the rafting of γ' phase under the influence of stress and temperature.

The creep damage model[19] considering cavitation and degradation together is described as follows:

$$\begin{aligned} \dot{\gamma}^{(\alpha)} &= \dot{\gamma}_i \left(\frac{1}{1-\varpi}\right)^n \mathrm{e}^S \\ \dot{\varpi} &= \dot{\varpi}_0 \dot{\gamma}^m \\ \dot{S} &= C\dot{\gamma}^p \end{aligned} \quad (5)$$

where, $\dot{\gamma}_i = \dot{\gamma}_0 \tau^n$, $\dot{\gamma}$ denotes the resolved shear creep strain rate, ϖ is cavitation damage factor and S represents the material degradation. $\dot{\gamma}_0$ is the initial creep strain rate, $\dot{\varpi}_0$ the initial damage rate. n, m, C and P are the model parameters, which depend on temperature.

In order to measure the damage level of material degradation, the equation is defined as follows:

$$D_S = \left(\frac{S}{1+S}\right)^r \quad (6)$$

In the present work, r=1.

The total damage is expressed as follows:

$$D = D_S + \varpi \quad (7)$$

If D=1, it means the material fracture.

2 Model and Parameters

In order to make comparative analysis of the creep behaviors of slant-angled film cooling holes, the plate specimens with cooling holes were chosen. As shown in Fig.1, the holes slant at a horizontal angle of α, given in Table 1. Uniaxial symmetric boundary conditions are applied with uniform tensile stress σ. The radius of the hole is R=0.2 mm. A-A is the middle cross section. The simulation was conducted at 900 °C using nickel based single crystal superalloys DD6. The analysis was performed along the crystallographic orientation [001]. All calculations were carried out on the three-dimensional models and hexahedral elements.

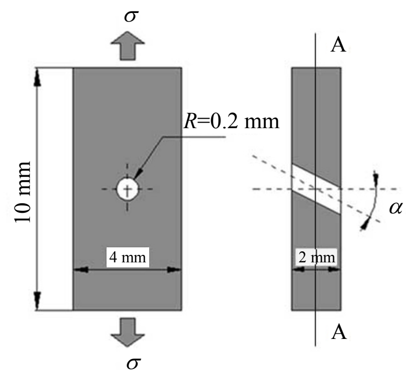

Fig.1 Plate model with slant-angled film cooling hole

Table 1 Four cases with different slant angles α of film cooling hole

Specimens	Case 1	Case 2	Case 3	Case 4
α/(°)	0	15	30	45

3 Results and Discussions

3.1 Influence of slant angle on failure life and resolved shear stress distribution

Four cases with different slant angles were investigated to obtain the effect of slant angle on creep failure life and resolved shear stress distribution. Table 2 gives the creep failure life which is defined as the cavitation stop time when the creep damage D of one element reaches 1.0. It can be found that the hole can be seriously adverse to the creep behavior of the crystal and the slant angle of the hole plays an important role in the adverseness to a considerable extent. From Table 2 we can observe an interesting phenomenon that the failure life is increasingly long when the slant angles are 0°, 15° and 30°, but when the slant angle is α=45°, the failure life decreases severely to 27.29 h. It is obvious that the failure life of holed-specimens decreases seriously compared with that of