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Effect of film-hole configuration on creep rupture behavior of a second generation nickel-based single crystal superalloys

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ABSTRACT

Thin-walled specimens with different film-hole configurations were used to model a second generation nickel-based single crystal superalloy. The effect of film-hole configuration on the high temperature creep rupture behavior of the superalloys was experimentally studied at 980 °C/300 MPa. A creep numerical model based on the crystal plasticity theory was built and implemented into a finite element procedure. A new factor was introduced in this paper to quantitatively characterize the stress multiaxiality. Experimental results show that one- and two-row specimens exhibit longer lives than those without film-holes. However, the creep rupture life decreases with the increase of film-hole rows. Stress distribution of different types of specimens was obtained by finite element analysis (FEA). Numerical results reveal that the existence of film-holes causes stress concentration and changes local stress from uniaxial to multi-axial. A variety of high temperature oxidation products were observed on the surface of the specimens, which could be a detrimental factor contributing to creep rupture. Numerical results were consistent with the fracture position and morphology of specimens of the experiment.

1. Introduction

Nickel-based single crystal superalloys (SXs) have been widely used in hot section components (mainly gas turbine blades) because of their excellent performance against high temperature creep in the past few decades. Decisive factors in creep of single crystal superalloys are chemical composition [1,2], crystallography [3,4], orientation [5,6], microstructure [7,8], temperature [9], stress [6], and the geometry of the component. Among these, the geometric factor, which has not received much attention, is the focus of the current paper.

Cassenti [10] observed that the creep response is larger in the thin wall SXs structures than in test specimens typically used to characterize the material and creep rupture lives obtained at moderate to high temperatures decreased sharply (about 60%) with a reduction in specimen thickness by approximately eight times. Lukas [11] performed creep tests on smooth and notched specimens of SXs (CMSX-4) of various orientations. The results show that the notched specimens exhibit a longer creep rupture life than the smooth specimens under the same minimum-section stress. Mao [12] used specimens with a single hole to study the evolution of plasticity for SXs cooled blade with film-holes by means of the crystal plasticity FEA and experimental observations. It is shown that the stress fields form four banded stripes around the hole, on which the initiation and propagation of the cracks are experimentally proved to be dependent. Yu [13] studied the creep damage evolution in a modeling specimen of SXs with 14 film-holes and both the experimental and the FEA results revealed that the creep damage is localized in the film-holes region, where the fracture will occur easily. Besides, it was proved by numerical calculations that specimens of SXs with different slant-angles of film-holes have different damage distributions and thus different crack propagation directions [14]. The studies above have indicated that the geometry of specimens have considerable effect on creep rupture properties of SX components.

With film cooling widely used as an active cooling method for higher thermal efficiency in practical applications, many studies have been conducted to understand the physical phenomena regarding the film cooling process and to find better film-hole configurations that can provide more protection with minimal amount of coolant. However, to the authors knowledge, no studies are found to investigate the effect of film-hole configurations on creep behavior of SXs.

The aim of this paper is to present experimental and numerical results on the film-hole configuration effects in the case of a second generation nickel-based single crystal superalloy DD6. To achieve the above goals, the thin-walled specimens with 0-4 rows of small holes were used to model the air-cooled turbine blades. And creep test at 980

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Table 1
Nominal chemical compositions of DD6 alloy.

Co	W	Ta	Al	Cr	Re	Mo	Nb	Hf	Ni
9	8	7.5	5.6	4.3	2	2	0.5	0.1	Balance

°C were carried out in crystallographic orientation [100] to investigate the influence of this geometric factor on the creep rupture behavior of DD6 air-cooled turbine blades. To understand the mechanism of how film-hole configuration has influence on the creep behavior of the DD6 specimens, finite element analysis was also performed. Finally, the comparison of the experimental and numerical results and several main conclusions is presented.

2. Experiment

The materials studied in this investigation are the nickel-based single crystal superalloys DD6. The chemical composition is given in Table 1.

Single crystals were kindly provided by Beijing Institute of Aeronautical Materials, China. All the materials tested came from cast cylindrical bars (about 80 mm in diameter) in fully heat treated condition (1290 °C × 1 h + 1300 °C × 2 h + 1315 °C × 4 h/AC + 1120 °C × 4 h/AC + 870 °C × 32 h/AC). The microstructure of the as-received bars is shown in Fig. 1 [15], which consist of cuboidal γ' precipitates embedded in a γ matrix. The size of γ' particles is 400–700 nm and the volume fraction of the precipitate phase is around 65%. All the tested specimens are [001] oriented (the relative crystallographic orientation error of the [001] oriented specimens was well controlled below 10°).

Five types of thin-walled specimens were designed and machined from the single crystal cast bars, namely specimens with 0, 1, 2, 3 and 4 rows of film-holes respectively as shown in Fig. 2, Fig. 3, Fig. 4 and Fig. 5. Each kind of specimens had a total length of 46 mm, a uniform thickness of 1.5 mm and a gauge of 10 mm in length and 3 mm in width. The specific values of constant parameters in Fig. 4 are given in Table 2. The film-holes, with the radius of 0.15 mm, were punched with electronic discharge machine (EDM). The final operation of machining was in each case a fine grinding.

The four types of film-hole configurations are designed according to the following conditions: (1) the total number of film-holes are the same of 10 for all specimens (the extra two film-holes for the four-row configuration are added to even the film-hole distribution); (2) $d1$ denotes the spacing of film-holes in the same row, $d2$ denotes the smallest distance between two film-holes in the neighboring rows, H denotes the spacing of film-hole rows, $L1$ and $L2$ denote the distance of first row and last row from the edge of the specimen respectively; (3) all the film-holes are as evenly distributed in the same part of the gauge area as possible. The specific data for film-hole configurations are shown in Table 2.

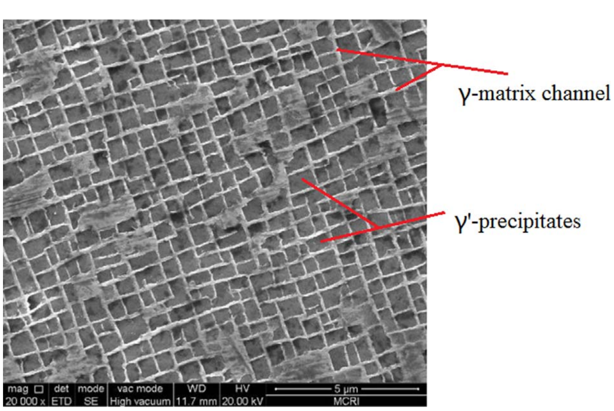

Fig. 1. Microstructure of nickel based single crystal superalloys. This figure is from reference [15].

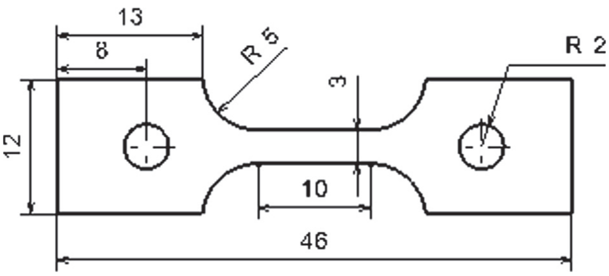

Fig. 2. Creep specimen diagram.

Fig. 3. Creep specimen without film-holes.

To exclusively investigate the influence of film-hole configuration (namely the number of film-hole rows) on the creep behavior and creep rupture life of the specimens, all the creep tests reported here were performed in air at a constant temperature of 980 °C under a constant load regime in tension, namely, at an initial maximum nominal stress (net section stress) of 300 MPa. In order to achieve constant nominal load, specimens with 0–4 rows of film-holes were applied different loads of 75 MPa, 67.5 MPa, 60 MPa, 60 MPa and 60 MPa in sequence. The elongation was continuously measured by means of linear variable differential transformers coupled with a digital data acquisition system.

3. Modeling

3.1. Creep constitutive law

The creep model is based on the pioneering single crystal plasticity theory of Rice et al. [16] and Peirce et al. [17]. Here, we assume that the creep deformation does not affect elastic deformation [16], and then

$$\Delta\sigma = D^e \Delta\varepsilon \tag{1}$$

where $\Delta\sigma$, $\Delta\varepsilon$ and D^e are the stress increment, the strain increment and the elastic stiffness tensor, respectively. And

$$\Delta\sigma = \{\Delta\sigma_{11} \quad \Delta\sigma_{22} \quad \Delta\sigma_{33} \quad \Delta\sigma_{12} \quad \Delta\sigma_{13} \quad \Delta\sigma_{23}\}^T \tag{2}$$

$$\Delta\varepsilon = \{\Delta\varepsilon_{11} \quad \Delta\varepsilon_{22} \quad \Delta\varepsilon_{33} \quad \Delta\varepsilon_{12} \quad \Delta\varepsilon_{13} \quad \Delta\varepsilon_{23}\}^T \tag{3}$$

In the crystal coordination ([001]-[010]-[100]), D^e can be written as:

$$D^e = \begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix} \tag{4}$$

where C_{11}, C_{12} and C_{44} are functions of elastic modulus E, Poisson's ratio μ and shear modulus G, that is:

$$C_{11} = E, \quad C_{12} = -\mu E, \quad C_{44} = G \tag{5}$$

The transformation relationship between the local crystallographic coordinate system ([001]-[010]-[100]) and the global coordinate system (o-x-y-z) is: