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Notch effect and its mechanism during creep rupture of nickel-base single crystal superalloys

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ABSTRACT

In this research, the double notched plate mini-specimens have been designed to study the notch effect during creep. The experimental results show that the notch has strengthening effect. The scanning electron microscopy (SEM) photos of fractured surfaces reveal that void growth is the primary mechanism of creep rupture. Finite element analysis (FEA) with a modified form of Kachanov–Rabotnov damage law was carried out to simulate the damage evolution in the specimens. The creep damage calculations show that the creep is a process of stress redistribution. The 3-D voided unit cell model with the constant maximum principal stress was used to explore the mechanism of notch strength. The results show that the initial stress triaxility has remarkable influence on void growth. The greater the initial stress triaxility is, the slower the growth rate is. The stress state plays a main role in void deformation. The void grows remarkably in transverse direction when the stress triaxility is high. The void growth and coalescence is the main mechanism of creep rupture. The multiaxial stress state can inhibit the void growth, and this constraint effect is beneficial to the creep life.

1. Introduction

Due to excellent high temperature mechanical properties, nickel-base single crystal superalloys have been widely used for advanced turbine blades. Having no grain boundary, single crystal turbine blades are mainly evaluated for their creep properties. Because they are of complex shapes, turbine blades are always under complicated stress conditions. Then to evaluate the material strength in the multiaxial stress zone, notch effect is referred to [1–5]. So far, much work has been done in the study of notched specimens. Sugimoto et al. [1] and Koji [2] both studied the tensile creep behavior of the single crystal notched plane plate specimens and reached the same conclusion: the creep stress of the notched plane plates is related to both the tensile direction and the plate normal crystal orientation. Basoalto et al. [3] studied the complicated stress conditions in the notched zone of plane plates and predicted the life of single crystal superalloys. Lukáš et al., [4] studied the creep properties of different orientations of CMSX-4 single crystal smooth and notched specimens, and found that the creep life of notched specimens is longer than that of smooth ones, which shows that the notch has strengthening effect.

In the past thirty years, the void nucleation, growth and coalescence in ductile fracture of polycrystalline metals has received extensive attention [6–15]. Cell models are mainly established for finite element analysis of void growth and coalescence. The void growth in matrix is closely related to the stress state of the model, the properties of the matrix material and the arrangement pattern of the voids. In single crystal materials, the void growth and coalescence is mainly related to crystal orientation, the stress triaxiality and the cumulative plastic strain [16,17]. Under creep conditions, void growth leads to the tertiary creep stage and eventually the fracture [18]. Studies have shown that void growth is the important mechanism of the creep and fracture of nickel-base single crystal superalloys [19,20].

In this paper, self-designed small specimens of double notched plates are used to study the notch effect under creep conditions, and finite element analysis is carried out to evaluate the stress and damage distribution during the creeping process of notched specimens. Cell models are established to simulate the stress state of the unit cell at the notch root to carry out an analysis of the strengthening effect of the notches.

2. Creeping experiments of the notched plates and the results

To study the notch effect on creep of nickel-base single crystal superalloys at 950 °C, as shown in Fig. 1, plane plate and double

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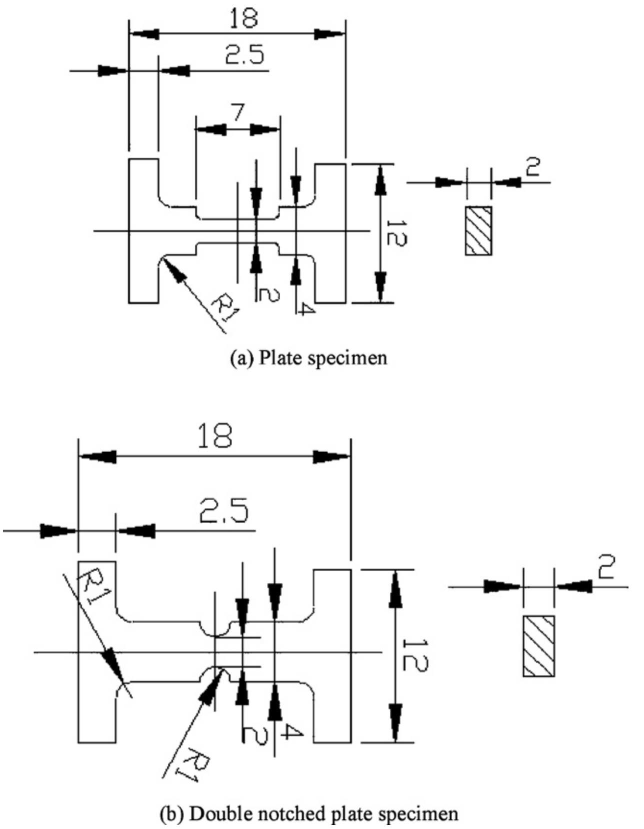

Fig. 1. The creep specimens; (a) Plate specimen and (b) Double notched plate specimen.

notched plate specimens were designed. The notch radius is 1 mm. The specimens were cut from nickel-base single crystal CMSX-4. The crystallographic orientation along the tensile direction is [0 0 1], and side facet is [1 1 0]. The experimental parameters and results are shown in Table 1 and Fig. 2, in which the stress is that in the minimum cross-section, and the displacement is that of the cross-beam of the testing machine.

As is shown above, the creep life of double notched specimens is longer than that of plane plate specimens. When stress is 500 MPa, the creep life of notched specimens increased by 20% compared with that of plane plate specimen; when the stress is 550 MPa, the creep life of notched specimens increased by 33% and 65% compared with that of plane plate specimen. The results, consistent with those of the Lukâs circumferentially notched specimens, suggest that notches have strengthening effect on the specimens.

Fig. 3 shows the SEM photos of the fracture surfaces. The fracture surface is made up of small facets, and surrounding the central parts of the facets are small cavities, and around the cavities microcracks can be easily found, as is shown in Fig. 3(a). It is found that the growth of small cavities is the primary mechanism of the creep damage. During the casting of the nickel-based single crystal superalloys, the defects such as cavities and inclusions cannot be avoided,

Table 1
The experimental parameters and results.

No.	Load(kN)/Stress(MPa)	Creep life/h	Notched
1	2.0/500	9.8	No
2	2.2/550	4.8	No
3	2.2/550	7.9	Yes
4	2.0/500	11.7	Yes
5	2.0/500	11.9	Yes
6	2.31/550	6.4	Yes

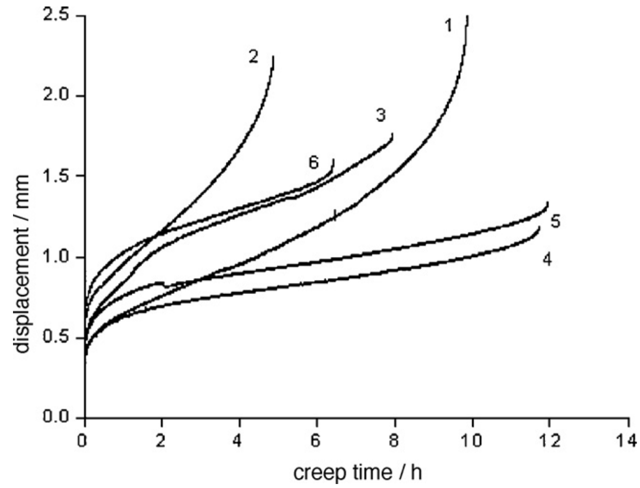

Fig. 2. Displacement–creep time curves.

which play an important role in the deformation, damage and fracture of these materials.

3. Finite element analysis of the creep damage

Generally, the existence of notches produces stress concentration, so the nearby parts of the notches are under complex stress state. During the creep process, stress is redistributed. To study the changes of the stress surrounding the notches, the modified K–R damage mechanics equations are employed [21,22]. The creep shear strain rate of the α slip system can be written as

$$\dot{\gamma}_c^{(\alpha)} = A\left(\frac{\tau^{(\alpha)}}{1-\omega^{(\alpha)}}\right)^n \tag{1}$$

$$\dot{\omega}^{(\alpha)} = B\left(\frac{\tau^{(\alpha)}}{1-\omega^{(\alpha)}}\right)^m \tag{2}$$

In which $\dot{\gamma}_c^{(\alpha)}$, $\dot{\omega}^{(\alpha)}$ and $\tau^{(\alpha)}$ are resolved shear strain rate, damage rate and resolved shear stress of slip system α, respectively; A, B, n and m are material constants and their values are listed in Table 2 which has ever been used by the authors in [23]. $\tau^{(\alpha)}$ can be calculated from the applied stress σ_{ij}

$$\tau^{(\alpha)} = \sum_{i=1}^{3}\sum_{j=1}^{3}\sigma_{ij} m_i^{(\alpha)} s_j^{(\alpha)} \tag{3}$$

where $m_i^{(\alpha)}$ and $s_i^{(\alpha)}$ are the i-th components of the slip direction vector and the slip normal vector of slip system α, respectively. The creep strain $(\varepsilon_{ij})_c$ can be calculated from the shear creep strain by

$$(\varepsilon_{ij})_c = \sum_{\alpha=1}^{n}\frac{1}{2}\gamma_c^{(\alpha)}(m_i^{(\alpha)} s_j^{(\alpha)} + m_j^{(\alpha)} s_i^{(\alpha)}) \quad (i, j = 1, 2, 3) \tag{4}$$

The maximal resolved shear stress of the slip system is defined as

$$\tau_{\max} = \max\{|\tau^{(\alpha)}|\} \tag{5}$$

Table 2
The creep damage parameters used in [23].

A	B	n	m
2.8395×10^{-17}	8.2369×10^{-17}	5.9925	5.8525