Materials Science & Engineering A 613 (2014) 184–192

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

# Influence and analysis of defects on creep behaviors of a single crystal nickel-based superalloy

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ARTICLE INFO

*Article history:*
Received 14 May 2014
Received in revised form
20 June 2014
Accepted 25 June 2014
Available online 2 July 2014

*Keywords:*
Single crystal nickel-based superalloys
Cavity with/free-crack
Creep lifetimes
FEM analysis

ABSTRACT

By means of creep properties measurement and microstructure observation, combined with the finite element method analysis, an investigation has been made into the influence of the cavity with/free cracks on creep behaviors of a single crystal nickel-based superalloy. Results show that during creep, the different evolution features of $\gamma'$ phase occur in the regions near the cavity with/free cracks in the single crystal nickel-based superalloy due to the various stress distributions. Therefore, the rafted $\gamma'$ phase in the region near the round cavity is transformed into the rafted structure along the direction of 45° angles relative to the stress axis, and the rafted $\gamma'$ phase in the region near the cavity-crack is arranged along the direction parallel to the round edge of the cavity in the form of the streamlined model due to the effect of the stress distribution. Compared to the stress value in the region near the round cavity, the bigger von Mises stress value is distributed in the pole **b** region near the cavity-cracks, and the maximum value of the stress distribution in the pole **b** region increases as the creep goes on, which may promote the propagation of the cracks along the direction perpendicular to the stress axis. This is thought to be the main reason for the alloy with the cavity-crack having a shorter creep life.



## 1. Introduction

The microstructure of single crystal nickel-based superalloys consists of the cuboidal $\gamma'$ phase embedded coherent in $\gamma$ matrix [1–3], and they have been widely used for preparing the blade parts of the advanced aero-engine due to high volume fraction of the $\gamma'$ strengthening phase and excellent mechanical and creep properties at high temperature [4–6]. With the increase of service performance, such as the aero-engine power and thermal efficiency, the mechanical and creep properties of superalloys at high temperatures need to be further improved [7–9].

Some investigations indicate that one of the most striking characteristics during high-temperature creep of single crystal nickel-based superalloys is the directional coarsening of the cuboidal $\gamma'$ phase to form preferentially orientated rafts, which has an obvious effect on the creep properties of alloys [10,11]. Especially, during creep at high temperature and low stress, the cuboidal $\gamma'$ phase in [001] oriented single crystal nickel-based superalloys transforms into the N-type rafted structure along the direction perpendicular to the stress axis, which can effectively hinder dislocation motion to improve the creep resistance of superalloys [12–14]. Although the single crystal nickel-based superalloys possess excellent mechanical and creep properties at high temperature, the centrifugal force originated from high speed rotation in aero-engine in service still may cause the creep damage of the blade parts, which is thought to be the main model of aero-engine failure [15–17].

The microstructure and creep feature of the single crystal superalloys change with imposed stresses and temperatures. Under the conditions of the applied stress of 552 MPa at 850 °C, some alloy during creep displays an incubation period in which some dislocations are piled up in $\gamma$ matrix channels [18]. In the primary stage of creep, the activated dislocations overcome the Orowan resistance to slip along the $\langle 110\rangle$ direction on the $\{111\}$ planes in the $\gamma$ matrix channel [19]. And some slipping dislocations in the same channel may react to form the dislocation networks which are located in the interfaces of $\gamma'/\gamma$ phases. Furthermore, the creep dislocations in the matrix move to the $\gamma'/\gamma$ interfaces under applied stress, and then react with the networks, so that the resolved segments change the original moving direction to promote the climbing of dislocations over the rafted $\gamma'$ phase during steady state creep of the alloy [20]. But with the enhancement of creep temperature, the interfacial dislocation to induce shearing $\gamma'$ phase becomes progressively easier, because of the decrease of elastic energy and the increase of diffusivity [21]. And the cavities and micro-cracks are initiated and propagated along the interfaces of $\gamma'/\gamma$ phases in the later stage of creep [22].

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http://dx.doi.org/10.1016/j.msea.2014.06.095
0921-5093/

During the preparation of single crystal parts, the local regions in the blade parts may form some defects due to the difference of the solidification conditions, such as the cavities, inclusions and micro-cracks etc. [23,24]. The defects destroy the continuity of microstructure in the alloys for affecting the transmission of stress under loading, which causes easily the stress concentration [25,26] to promote the initiation and propagation of cracks for reducing the creep life of the single crystal superalloys [27]. But the features of the stress distribution around the inclusions or cavities and their effect on the creep behaviors and microstructure evolution during creep are not clear. Especially, the cavities with different configurations may cause the various stress distributions during creep, so that results in the different creep life and various evolution features of microstructure.

The influence of the stress distribution in the region near the cavity with various configurations on the damage of the specimen during creep may be evaluated by means of the finite element method [28]. Compared to the stress distribution in the region near the cavity in the single crystal alloy, the complex distribution regularity of the stress field occurs in the region near the cavity in the poly-crystals alloys [29]. But no literatures report the influence regularity of the defects with various configurations on the microstructure evolution and creep properties of alloys.

Hereby, in the paper, by means of creep properties measurement and microstructure observation of single crystal nickel-based superalloy containing the cavity with/free cracks, an investigation has been made into the influence of the defects on the microstructure evolution of $\gamma'$ phase and creep properties of the alloy, based on analyzing the regularity of the stress distribution in the region near the cavity with/free cracks by means of the finite element method (FEM).

## 2. Experimental procedure

The bars of single crystal nickel-based superalloy with [001] orientation had been produced by means of selecting the crystal method in a vacuum directional solidification furnace under the condition of a high temperature gradient. Longitudinal orientations of all specimens were measured to be within 7° deviating from [001] orientation by Laue back reflection method. The nominal chemical composition of the alloy is NI-6.0Al–6.5Cr–6Mo–6.0Co–6.5Ta–7.5W (mass fraction, %). The used heat treatment regime is given as follows: 1280 °C, 2 h+1315 °C, 4 h, A. C+1050 °C, 4 h, A. C.+870 °C, 24 h, A. C.

After full heat treatment, the bars of single crystal superalloy were cut into the plate-like creep specimen with cross-section of 4.5 mm × 2.5 mm and gauge length of 20.0 mm along the [001] orientation. The wider surface of the specimens is parallel to (100)

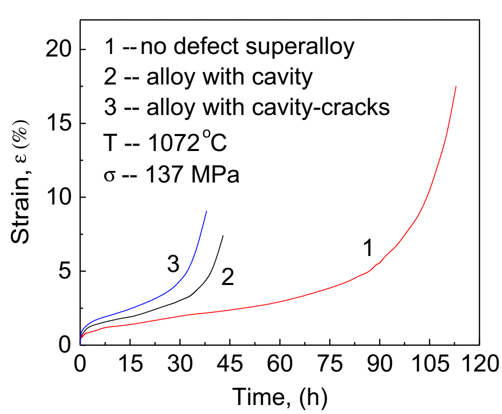


**Fig. 1.** Influence of the defects on creep properties of the alloy.

crystal plane. After mechanical grinding and polishing, the specimens with/free defects are placed into the creep testing machine with model GTW504 type; a uni-axial constant load tensile testing was performed under the applied stress of 137 MPa at 1072 °C. The microstructure of the specimens after being crept up to fracture is observed by using scan electron microscope (SEM). The stress distribution in the region near the cavity with/free cracks is analyzed by means of the finite element method (FEM), and the influence of the stress distributions on the microstructure evolution regularity and creep life of the single crystal superalloy at high temperature is investigated.

## 3. Experimental results and analysis

### 3.1. Creep feature and microstructure evolution of alloy

Due to the in-homogeneity of microstructure in the local region of the alloy during solidification, some cavity defects appear in the inter-dendrite regimes of single crystal nickel-based superalloys. During creep at high temperatures/lower stress conditions, the cavity defects formed during casting and solidification destroy the continuity of the microstructure to bring easily the stress concentration, which may obviously reduce the creep life of the alloy at high temperature. Under the applied stress of 137 MPa at 1072 °C, the creep curves of the single crystal superalloy with/free cavity defects are measured as shown in Fig. 1.

The creep curves of the single crystal nickel-based superalloy with/free cavity defects are marked by the numbers 1 and 2 in Fig. 1, respectively, and the creep curve of the single crystal superalloy with the cavity plus cracks is marked by the number 3. It is indicated according to the comparison of the creep properties that the defect-free alloy displays a lower strain rate during steady state creep and longer creep life, the creep life of the alloy is measured to be 113 h and the strain value of the alloy is about 17%. The creep life of the alloy with cavity defect is measured to be 43 h, the strain value of the alloy creep up to fracture is about 7.5%, and the creep life of the alloy with cavity-crack defect is measured to be 38 h. This indicates that the cavity defects formed during solidification may obviously decrease the plasticity and life of the alloy during creep.

The microstructure of as-cast single crystal nickel-based superalloy consists of the $\gamma$ matrix and $\gamma'$ phases with inhomogeneous size, as shown in Fig. 2(a), the $\gamma'$ precipitates with smaller size of about 0.5 μm are distributed in the dendrites arm region, as shown in Fig. 2(b), and the ones with bigger size of about 2 μm are distributed in the inter-dendrite region, as shown in Fig. 2(c).

After solution at high temperature and full heat treatment, the microstructure of the alloy consists of the cuboidal $\gamma'$ phase embedded coherent in the $\gamma$ matrix, as shown in Fig. 3. The normal direction of the film surface is the [001] orientation, the gray areas in Fig. 3 correspond to the cuboidal $\gamma'$ phase in the alloy, while the black areas correspond to the $\gamma$ matrix phase, which indicates that the average size of the cuboidal $\gamma'$ phase in edge is about 0.4–0.45 μm, the width of $\gamma$ matrix channel is about 80–100 nm. The cuboidal $\gamma'$ phase in the alloy is regularly arranged along the ⟨100⟩ direction, the volume fraction of the cuboidal $\gamma'$ phase is about 68%. And it is thought that the creep resistance of the alloy increases with the volume fraction of the cuboidal $\gamma'$ phase.

After full heat treatment, the microstructure of the alloy with the round cavity is shown in Fig. 4; it is indicated that the size of the round cavity is about 8 μm, and the cuboidal $\gamma'$ phase around the cavity is regularly arranged along the ⟨100⟩ direction.

After the defect-free alloy is crept for 40 h under the applied stress of 137 MPa at 1072 °C, the microstructure of the alloy is