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The effect of microstructure on the creep behavior of a low rhenium-containing single crystal nickel-based superalloy

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ABSTRACT

A low rhenium-containing single crystal nickel-based superalloy designated DD6 with different γ′ morphologies induced by discrepant aging treatments crept at 1100 °C/137 MPa and 850 °C/660 MPa. The test results and TEM observations showed that creep mechanism varies with microstructure and test temperature. For creep at 1100 °C/137 MPa, the dislocation network on γ/γ′ interface plays a key role in prolonging creep life. The sample with the lager cubical γ′ precipitate got the longest rupture life. For creep at 850 °C/660 MPa, the morphology of γ′ phase and the width of the γ channels dominate the deformation behavior. The sample with smaller γ′ particles and narrower γ channel exhibited the highest creep life due to the inhomogeneous activations of multiple ⟨112⟩ {111} slip systems.
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1. Introduction

For decades, single crystal (SC) nickel-based superalloys have been widely used for turbine blade applications in modern aviation engines and gas turbine systems due to their high temperature capability. The superior strength and high temperature resistance of this kind of SC alloy are attributed to its high volume fraction of regularly aligned cubical γ′ precipitates coherent with γ matrix [1,2]. Ordered Ni_3Al (γ′ phase) has $L1_2$ structure. The γ′ phase offers the SC superalloy high temperature strength and occupies up to 70 vol% for the most advanced superalloys. In recent years, many efforts have been made to enhance the high temperature properties of these alloys in order to improve the thermal efficiency in modern turbine industries, including the successful development of some new-generation SC superalloys [3–5]. However, these so-called 3rd, 4th and 5th generation SCs generally contain high percentages of costly refractory elements like Re and Ru, which play critical roles in the improvement of the high temperature strength for these newly designed superalloys. The costly Re could result in the difficulty of solution heat-treatment and forming topologically close-packed phases (TCP) which are harmful to high temperature properties [6]. In order to solve the above problems, efforts have been made in following aspects: (1) developing new single crystal alloys using low Re and maintaining the mechanical properties close to those of the single crystal alloys with high Re contents, (2) optimizing the microstructures of the existing SC superalloys by adjusting heat-treatment to upgrade their high-temperature properties [7,8]. Many researches have been made on the effects of microstructure and different compositions on high temperature mechanical properties of superalloys [9–16]. DD6 alloy is a low cost 2nd SC superalloy developed by Beijing Institute of Aeronautical Materials with low Re and without Ru [17]. In this paper, our effort was to optimize the heat treatment of this SC, and few researches have been made on the microstructure dependent creep properties of this single crystal superalloy [18,19]. It is well known that the deformation mechanism for the Ni-based SC superalloy creep at high temperature and low stress is much different from the creep at intermediate temperature and high stress [11]. So the overall objective of this paper is to determine the role of microstructure on dislocation structure during creep and improving the creep properties of this low Re single crystal superalloy at both high and intermediate temperatures by optimizing heat treatment.

2. Experimental procedure

The nominal composition of DD6 single crystal superalloy studied in the present investigation is listed in Table 1. It contains

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lower rhenium compared to other second generation alloys such as CMSX-4 and René N5.

The single crystal rods were cast by the directional solidification using a helical selector. The orientation of each rod was determined by Laue back-reflection technique, and the rods with crystal orientations within 6–7° from the [001] direction were selected.

The as-casted rods were fully solution heat-treated at (1290 °C, 1 h)+(1303 °C, 2 h)+(1312 °C, 2 h)+(1320 °C, 15 h) to eliminate the segregation of compositions and subsequently first-step aged at different temperatures listed in Table 2. Different first-step aging rules were used in order to obtain various γ′ morphology (note that the standard aging treatment was used for N-2 SC superalloy). The last aging steps for the three samples were same in order to get the same volume fractions of γ′ phase for the alloy rods. Samples were polished and etched by 20 g $CuSO_4$+50 ml hydrochloric acid+100 ml distilled water for scanning electron microscopy operated on Jeol JSM 7600F.

Cylindrical specimen with gauge length of 25 mm and diameter of 5 mm was used for tensile creep tests. Tests were carried out at 1100 °C/137 MPa and 850 °C/660 MPa respectively for the samples along the [001] direction using a constant-load creep testing machine in air. Thin foils perpendicular to the load axis were cut from creep interrupted and ruptured samples. Discs were mechanically thinned to 0.05 mm and then electro-polished at −30 °C in 5% perchloric acid+ethyl alcohol solution. The foils were observed in Jeol JEM 2100 and Jeol JEM 2100F transmission electron microscopes operating at 200 kV.

Table 1
The nominal composition of DD6 single crystal superalloy (wt%).

Ni	Co	Mo	W	Al	Cr	Ta	Re	Hf
Bal.	9.0	2.0	8.0	5.7	4.3	7.5	2.1	0.1

Table 2
Heat-treatment applied to the experimental single crystal superalloy (A.C air cooled) and resulting average γ′ size.

No. of samples	Aging heat-treatment	Average γ′ size (nm)
N-1	(1000 °C)/2.5 h/A.C+(870 °C)/25 h/A.C	340
N-2	(1100 °C)/4 h/A.C+(870 °C)/25 h/A.C (standard)	420
N-3	(1180 °C)/0.5 h/A.C+(1150 °C)/4 h A.C+(870 °C) /25 h/A.C	513

3. Experimental results

3.1. Creep at 1100 °C and 137 MPa

The typical γ/γ′ microstructures of these SC superalloys after various aging heat treatments are illustrated in Fig. 1. It can be followed from Fig. 1 that the average size of γ′ precipitates in the N-1 SC sample is smallest and the morphology is irregular compared to N-2 and N-3 samples.

The creep curves for the samples crept at 1100 °C and 137 MPa are shown in Fig. 2 and their parameters are compared in Table 3. For the three differently aged SC samples, the N-3 exhibits the longest rupture life and the lowest secondary creep rate (steady creep rate), while N-1 shows the lowest. It is clear from Fig. 2(b) that N-1 has an incubation period compared to the other

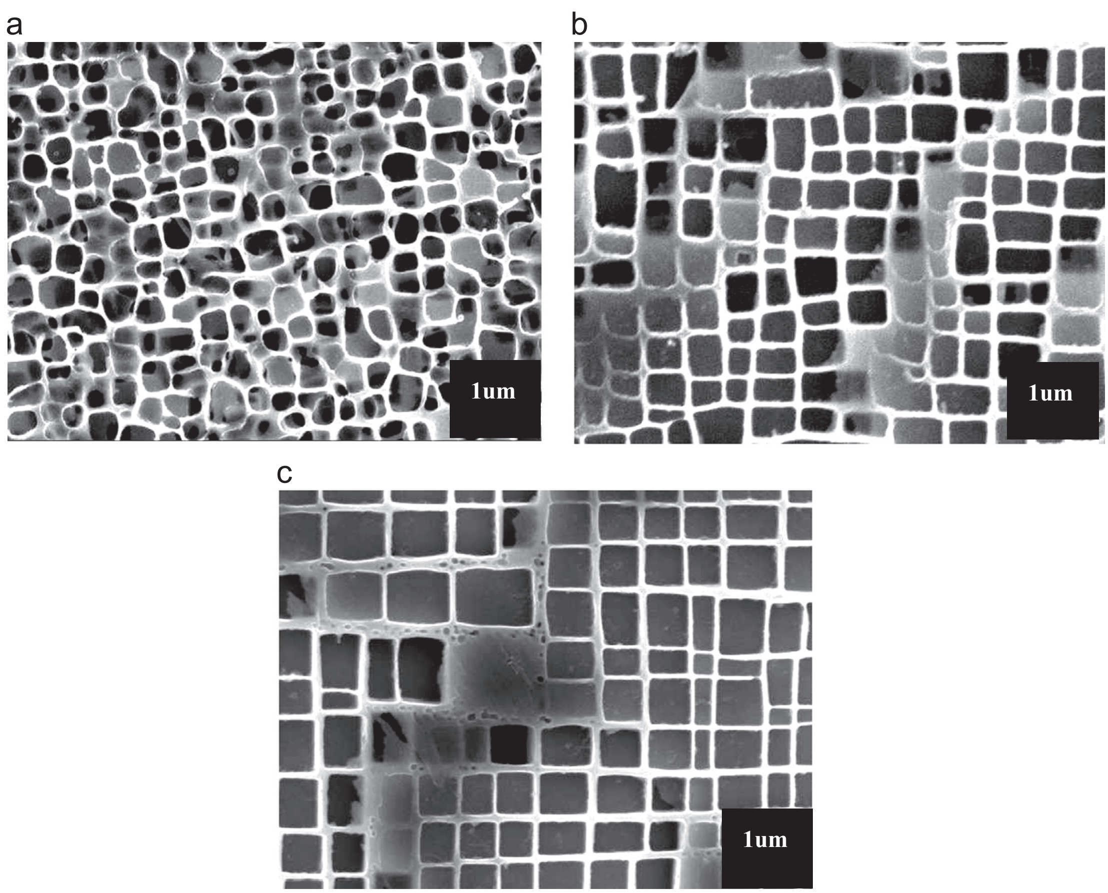

Fig. 1. The morphologies of γ′ precipitates of superalloys after various aging treatments: (a) N-1 sample; (b) N-2 sample; (c) N-3 sample.

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