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Anisotropy of stress rupture properties of a Ni base single crystal superalloy at two temperatures

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Abstract

The stress rupture properties of a single crystal superalloy in three orientations were tested under 871 °C/552 MPa and 1010 °C/248 MPa. The [0 0 1] orientation shows the longest life and good elongation at 871 °C, the [1 1 1] orientation exhibits the best elongation, while the life and elongation of [0 1 1] orientation are both poor at this test condition. At 1010 °C, the anisotropy between [0 0 1] and [0 1 1] orientation is evidently reduced, however the [1 1 1] orientation shows the longest life at the same condition. In [0 0 1] orientation, the N type rafts are formed under two test conditions. In [1 1 1] orientation, the γ' keep cuboidal shape under 871 °C/552 MPa, while rafts with direction varying with local position are formed under 1010 °C/248 MPa. In [0 1 1] orientation, lots of stacking faults appears in γ' under 871 °C/552 MPa, while many twins are formed under 1010 °C/248 MPa, which are both related to the activation of $\{1\,1\,1\}\ \langle 1\,1\,2\rangle$ slip system. The influence of orientation and test condition on the deformation mechanisms and stress rupture properties is discussed.

Keywords: Single crystal superalloy; Stress rupture; Precipitate; Anisotropy

1. Introduction

The single crystal superalloys are widely employed for gas turbine blade due to their excellent performance under extreme temperature and stress. The advantage of this material arises mainly from the fact that failures associated to grain boundary are precluded. As a direct result the stress rupture properties are remarkably enhanced. However, the deformation and fracture behavior are highly anisotropy. Some work has shown that the creep behavior at low temperature is significantly sensitive orientations, but the influence of orientation on creep properties reduce drastically at elevated temperature [1–4].

Nowadays, the turbine inlet temperatures can exceed the melting temperature of the alloy employed. This is achieved under the help of effective interior air-cooling and protective thermal barrier coating. Moreover, the complex air-cooling channels in the blade can also generate multi-axial thermal stress at the bottom of the blade within the intermediate temperature. Therefore, the operating temperature of the whole blade varies over a wide range from the highest at the top end down to the lowest at the root, thus it is necessary to study the anisotropy of stress rupture properties as well as related deformation mechanisms at different temperatures. In the paper of Leverant and Kear [5], the [1 1 1] orientation of Mar M200 exhibit superior creep properties at 760 °C/689 MPa than that of [0 0 1] because of low Schmid factor of $\{1\,1\,1\}\ \langle 1\,1\,2\rangle$ slip system to [1 1 1]. Sass et al. [6] reported that the [1 1 1] orientation of CMSX-4 alloy shows poor creep strength at 850 and 980 °C compared to [0 0 1] caused by poor strain hardening and occurrence additional cube slip. In addition to different active slip systems and Schmid factors the change of γ' morphology can also impose considerable influence on creep properties of different orientations. Therefore, this paper investigates the effect of orientation on the stress rupture properties of an experimental single crystal superalloy tested at 871 °C/552 MPa and 1010 °C/248 MPa, the micro-structural feature and dislocation configuration after tensile stress rupture in three elementary orientations. The relation between anisotropic stress properties and test conditions is also discussed.

2. Experimental procedures

The experimental single crystal superalloy in present work was used aiming to a high creep strength, its nominal composition is listed in Table 1, high contents of W and Ta are selected for both high temperature capability and density balance of liquid

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Table 1
Nominal composition of experimental alloy (wt%)

Cr	Co	W	Mo	Al	Ti	Ta	Ni
6	5	8	2	5	2	6	Bal

during directional solidification. The [0 0 1] rods are directionally cast by Bridgman method using selector technique, while the [0 1 1] and [1 1 1] rods are produced using correspondent seeds mounted in the mould. The heat treatment to the single crystal rods comprise a single step solution treatment (1305 °C/8 h) and a two step ageing treatment (1080 °C/4 h + 870 °C/24 h). The heat treatment produced cuboidal γ' particles with mean edge length of about 0.47 μm. The tensile stress rupture tests were performed in air at 871 °C/552 MPa and 1010 °C/248 MPa using constant-load creep testing machines. The gauge of cylindrical samples had a length of 25 mm and a diameter of 5 mm. The samples for observation of microstructure after rupture using SEM were prepared by grinding, polishing and then electro-etching using a solution of 5 g $(NH_4)_2SO_4$ + 5 g citric acid + 300 ml H_2O. Thin foils for TEM were prepared from the ruptured specimens. Discs were cut normal to the stress axis and 5 mm apart from the fracture, then mechanically ground to 50 μm and finally electro-polished at −20 °C in a solution of 7% perchloric acid and 93% ethanol. The foils were observed using Jeol 2000FX transmission electron microscope operated at 200 kV.

3. Results

3.1. Stress rupture properties

The stress rupture lives and elongations are illustrated in Fig. 1, each data is average of two specimens. It can be seen that the stress rupture properties are strongly influenced by orientations at both test conditions. The [0 1 1] samples show shortest lives at two conditions compared to the other two orientations, the most striking feature is that the longest live changes from [0 0 1] at 871 °C/552 MPa to [1 1 1] at 1010 °C/248 MPa. Additionally, the [1 1 1] exhibits the elongation maximum compared to the other two at intermediate temperature and the minimum at high temperature.

The comparison of stress rupture property between PWA1483 [7] and present alloy through Larson–Miller parameter is illustrated in Fig. 2. It can be seen that the stress rupture property of present alloy is equal to or higher than that of PWA 1483.

3.2. Microstructures after fracture

3.2.1. Microstructure after rupture at 871 °C/552 MPa

The γ' morphologies of three orientations ruptured at 871 °C/552 MPa are illustrated in Fig. 3. Some features can be seen from these pictures. Under this test condition, the γ' particles interlinked each other perpendicular to applied tensile stress in [0 0 1] orientation known as N type rafts [8], in the [0 1 1] orientation the rafts inclining about 45° angle to the stress are formed, while in the [1 1 1] sample, the γ' particles retain almost the previous cuboidal shape.

The dislocation configuration of three orientations ruptured at 871 °C/552 MPa are shown in Fig. 4. In the [0 0 1] orientation, dense dislocations fill the matrix channels, also some stacking faults can be found in γ' rafts. In the [0 1 1] orientation, besides high-density dislocations in matrix, a number of stacking faults appear in the γ' phases. On the contrary, no stacking fault is formed in γ' phase of [1 1 1] sample.

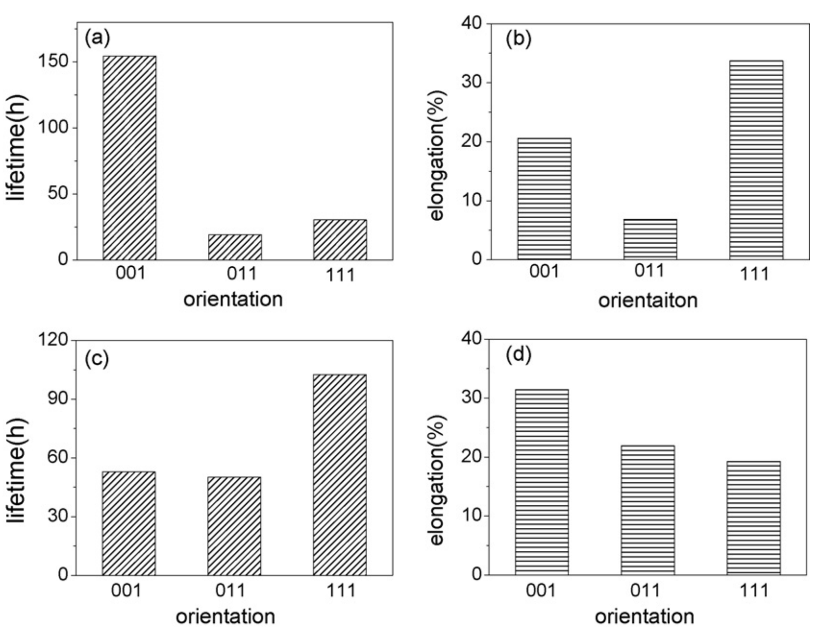

Fig. 1. Stress rupture properties of three orientations at two test conditions: (a) lives at 871 °C/552 MPa, (b) elongations at 871 °C/552 MPa, (c) lives at 1010 °C/248 MPa and (d) elongations at 1010 °C/248 MPa.