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Anisotropy of high temperature creep properties of a Co-base single crystal superalloy

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ABSTRACT

The orientation dependence of creep properties of a Co-base single crystal superalloy at 982 °C/248 MPa was investigated. The orientations of specimens tested were near [001, 011] and [111]. The results showed the deformation of these specimens was all controlled by a/3 < 112 > slip and stacking faults. The specimens with orientation near [001] exhibited the best creep resistance. There were a few stacking faults with two orientations in the specimens with [001] orientation. Specimens with orientations near [111] and [011] showed shorter creep lives, and stacking faults with single orientation were observed.

1. Introduction

Compared to the γ′-strengthened Ni-base superalloys, conventional Co-base superalloys generally exhibit superior corrosion resistance, thermal fatigue resistance and weld-ability. However, the high temperature strength of these classic Co-base superalloys cannot compete with the excellent high temperature properties of γ′-strengthened Ni-base superalloys [1,2]. Recently reported Co-Al-W-base alloys exhibit similar γ/γ′ two-phase microstructure, which can keep stable above 990 °C [3] and has comparable creep resistance to the first-generation Ni-base single-crystal superalloy at 900 °C. The γ′ solvus temperature was increased gradually by composition optimization, suggesting that the Co-Al-W-base alloys are promising candidates for high-temperature applications [3–5].

The creep properties of the Co-Al-W-base alloys along [001] orientation have been reported by previous researchers [4,6]. The creep rupture life exceeded those of commercial first-generation Ni-base single crystal superalloys at 982 °C/248 MPa [7]. The strengthening mechanisms generally found in Ni-base alloys such as γ′ rafting, shearing of γ′ precipitates with stacking faults (SFs) and antiphase boundaries (APB), and dislocation intersection in the γ′ precipitates were also observed in the Co-base alloy, which led to the improved creep resistance for the [001] orientation specimens [8].

Ni-base single crystal superalloys are known as anisotropy [9–11], especially for the creep properties tested at the condition of low temperature and high stress [10,11]. For example, the stress rupture lives of SRR99 at 760 °C/790 MPa were found as [001] > [111] > [011] (456 h, 20 h and 5 h, respectively) [12]. For the [001] oriented crystals, the dominant deformation mechanism was multiple a/2 < 110 > slip systems motion in horizontal channels (l/3 of matrix phase). For the [011] oriented crystals, the dominant deformation mechanism was related to the a/3 < 112 > dislocations cutting into γ′, which led to poor rupture properties. The dominant deformation mechanism of [111] orientations was multiple a/2 < 110 > slip systems motion, but in all channels (3/3 of matrix phase). γ′ phase was very rarely cut by SFs [13].

However, the anisotropy of creep behavior is not significant at temperature of ~1000 °C [13]. For example, the stress rupture lives of three orientations for SRR99 at 1040 °C/165 MPa were comparable (150 h, 185 h and 131 h for [001, 111] and [011], respectively) and [111] was the strongest orientation [12]. This is due to the change of dominant deformation mechanisms at high temperature. Climbing and cross slip of a/2 < 110 > dislocations in the matrix with the aid of thermal activation were the main deformation modes for all three different oriented specimens [12].

The new Co-base superalloy exhibits a significantly low SF energy compared to that of the Ni-base superalloys [14]. SFs cutting into γ′ were also observed at high temperature creep of [001] specimen [8]. This may change the interaction between the dislocation and γ′, and consequently affect the anisotropy behavior of the Co-base single crystal superalloys at high temperature. Therefore, in this study, the high-temperature creep behaviors and the deformation mechanism of a Co–Al–W–Ta–Ti single crystal alloy with different orientations were investigated.

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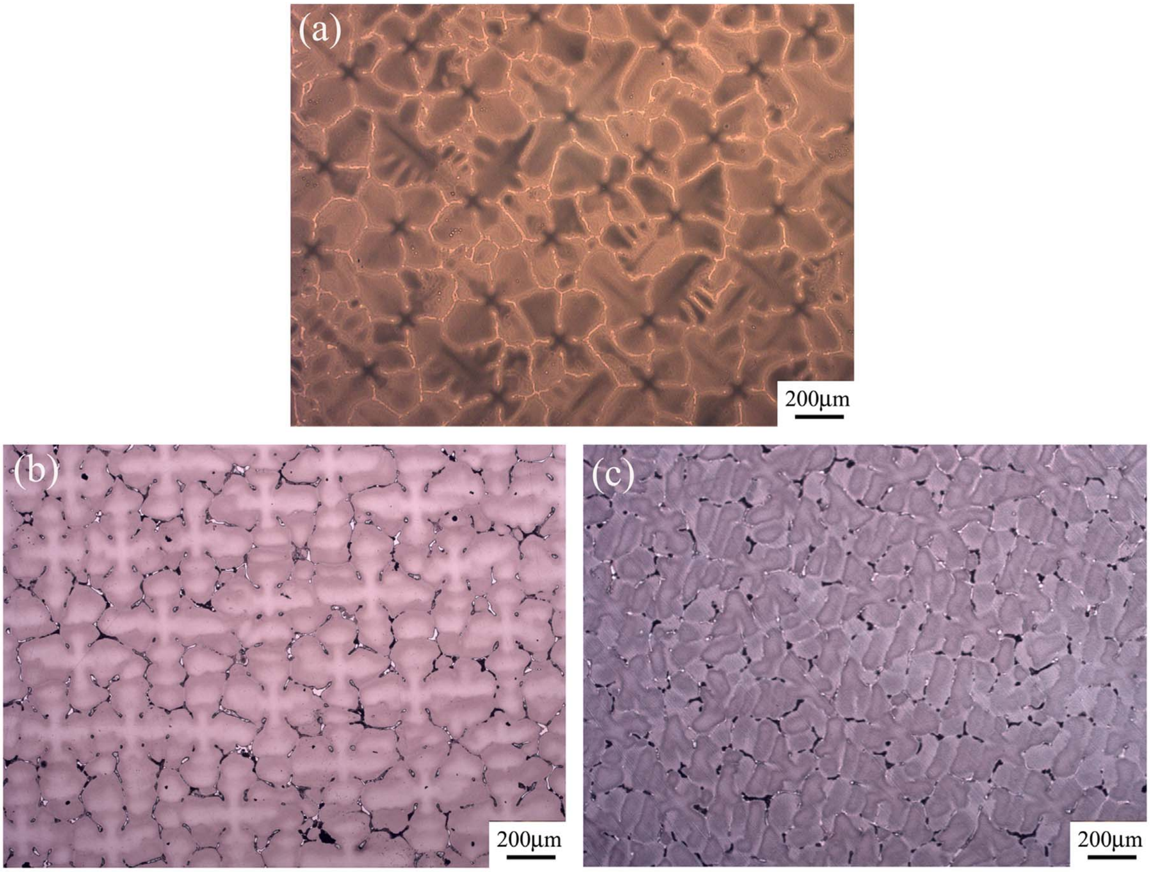

Fig. 1. The dendrite structures in the transverse sections of as-cast specimens with (a) [001], (b) [011] and (c) [111] orientations.

2. Materials and experimental procedures

The nominal composition of the experimental alloy is Co–7Al–8W–1Ta–4Ti (at%) [15,16]. The single crystal bars with [001] orientation, 16 mm in diameter and 220 mm in length, were prepared by grain selecting method. The method is widely used during directional solidification of single crystals. Only one grain with [001] orientation will finally survive through grain selector , and grow into the single crystal part. The single crystal plates with [011] and [111] orientations, 16 mm × 80 mm × 220 mm, were prepared by seeding method. A single crystal seed with [011] or [111] orientation was placed in the bottom of the mold to allow the epitaxial growth of the single crystal parts. The conventional Bridgman furnace was used. Then the castings were solution heat treated at 1270 °C for 24 h and subsequently aged at 900 °C for 50 h in the vacuum furnace.

Specimens with a 25 mm gage length and a diameter of 5 mm for different orientations were machined for creep test at 982 °C with a tensile stress of 248 MPa in air. Three specimens were tested for each orientation. The samples for electron back-scattered diffraction (EBSD) examination were cut from different locations of the ruptured specimens (near the screw and near the fracture), ground and electro-polished in a solution of 10% perchloric acid and 90% ethanol. The crystal orientation in the screw section can represent the orientation of the single crystal before testing since little orientation variation occurred during creep in this section. Microstructural observation of as-cast and heat-treated samples was conducted with an optical microscope and scanning electron microscopy (SEM). The γ' volume fraction was measured by the standard point count method. Specimens cut at a distance of 6 mm away from fracture surface were mechanically ground to 40 μm. Electron transparent thin foils were prepared by double jet electrochemical thinning in a TenuPol-5 at − 20 °C in a solution of 10% perchloric acid and 90% ethanol. They were then examined by a JEM 2100 transmission electron microscope (TEM).

3. Results and discussion

The average primary dendrite arm spacing in as-cast single-crystal alloy was measured to be 300 μm. The dendrite structures in the transverse sections were showed in Fig. 1. The dendrite morphologies were different for the three orientations. The eutectic pools were completely dissolved and the dendritic segregation was significantly reduced by solution treatment (Fig. 2a). The γ'precipitates exhibited cuboidal morphology with a volume fraction of 85% and a mean size of 0.25 μm in specimen with [001] orientation, but the γ'precipitates exhibited irregular morphologies in specimens with [011] and [111]orientations (Fig. 2b-d).

The creep properties and creep curves at 982 °C/248 MPa are shown in Fig. 3. Specimens with [001] orientation exhibited the longest creep lives of ~79 h and the best elongation ~34%, while the specimens with [011] orientation showed the minimum creep lives of ~35 h and elongation ~15% (Fig. 3a). Fig. 3(b) shows typical creep curves of the specimens with different orientations. Limited primary creep (< 0.2%) was observed in all specimens. The minimum creep rate was established within the first hour in all tests, and this rate persisted for 30–60 h, depending on the orientations. The creep strain of specimens with [001] orientation increased steadily in the first 60 h. Accelerated creep was then observed until fracture. The creep strains of [011] and [111] specimens were nearly unchanged during the whole creep stage. The strain rates were far lower than that of [001] specimen as shown in Fig. 3(b).

The fractured specimens and their orientations are compared in Fig. 4. Necking occurred in [001] specimen, and the fracture surface was roughly perpendicular to the applied stress. On the other hand, necking was less significant in [011] and [111] specimens. The fracture