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Improvement of stress–rupture property by Cr addition in Ni-based single crystal superalloys

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ABSTRACT

The effects of Cr addition on the microstructure and stress–rupture property have been investigated in three experimental Ni-based single crystal superalloys containing various levels of Cr addition (0–5.7 wt.%). The Re partitioning ratio increased and the lattice misfit became more negative with increasing the Cr addition in both dendrite core and interdendritic region. The changes of elemental partitioning behaviors and the lattice misfit show good agreement with the change of γ′ morphology. Cr addition increased the stress–rupture life at 1100 °C/140 MPa significantly due to higher γ′ volume fraction, more negative lattice misfit and a well rafting structure as well as less width of γ channels. High Cr addition (5.7 wt.%) increased the degree of Re and Cr supersaturation in the γ phase and promoted the formation of topologically close-packed (TCP) phases significantly under thermal exposure and creep deformation at 1100 °C.

1. Introduction

Ni-based single crystal superalloys have been used extensively for turbine blades in aircraft engines. Advanced Ni-based single crystal superalloys typically contain significant levels of refractory alloying additions such as Re, W, Ta and Mo in order to achieve a remarkable creep resistance at elevated temperature [1,2]. However, high levels of refractory alloying additions also result in an increased propensity for the formation of topologically close-packed (TCP) phases during high temperature thermal exposure [3,4]. TCP phases are detrimental to high-temperature performance of superalloys due to their brittle nature and depleting potent solid solution strengthening elements from the γ matrix. Chromium (Cr) is generally added to Ni-based superalloys because it is beneficial to hot corrosion and oxidation resistance [5]. However, high levels of Cr addition also result in detrimental TCP phases. In order to add more refractory alloying additions with keeping microstructural stability, modern commercial Ni-based single crystal [1] and directionally solidified [6] superalloys typically contain lower levels of Cr. In addition, Cr is an effective solid solution strengthener [5]. However, there were seldom systematic investigations on whether Cr addition has significant effect on high-temperature creep property of single crystal superalloys. Yoo et al. predicted the effect of Cr addition on the creep property of Ni-based single crystal superalloys using Bayesian neural network technique and indicated that the creep rupture life decreased with increasing levels of Cr addition [7], but they did not consider influence factors such as γ′ volume fraction and phase stability. Furthermore, the mechanism by which Cr addition influences the creep property of single crystal superalloys is still not well understood.

Early work regarding the effect of Cr addition on Ni-based single crystal superalloys suggested that Cr addition alter the partitioning behaviors of alloying elements (especially Re) between the γ and γ′ phases, and the Re partitioning ratio increased with increasing the Cr content [8–11]. The influence of Cr addition on the elemental partitioning ratio is of particular importance because of its close relationship with the γ/γ′ lattice misfit and γ′ morphology [12,13]. It is well known that the partitioning characteristics of alloying elements control both the sign and magnitude of lattice misfit, which determines the morphology of γ′ precipitates [12]. In addition, a non-zero lattice misfit is known to enhance the rafting process and increase the creep strength at high temperature and low stress because the rafting structure can be an effective barrier for confining dislocation activity within the γ rafts and leading to the steady state of the creep deformation, and the rafting direction is dependent on the direction of the applied stress and the sign of the lattice misfit [14]. Ni-based superalloys that raft perpendicularly to the applied tensile stress have a negative

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Table 1
Measured compositions of three investigated alloys (wt.%/at.%).

Alloy	Ni	Al	Ta	W	Co	Re	Cr
USTB-F1	Bal.	5.9/13.6	7.8/2.7	5.7/1.9	7.0/7.4	4.6/1.5	0
USTB-F2	Bal.	6.0/13.8	8.0/2.7	5.7/1.9	7.0/7.3	4.7/1.6	2.8/3.6
USTB-F3	Bal.	5.8/13.3	8.1/2.8	5.7/1.9	7.2/7.6	4.7/1.6	5.7/6.8

lattice misfit. And alloys with a positive lattice misfit raft parallelly to the applied tensile stress. If the lattice misfit is eliminated, the rafting should not occur. Recently, Carroll et al. reported that Cr addition (3.4–6.7 wt.%) resulted in higher Re partitioning ratio, more cuboidal γ′ precipitates and the corresponding better creep resistance at 950 °C/290 MPa [11,15]. However, systematic investigations were limited regarding the influence of Cr addition on the γ′ morphology, γ/γ′ elemental partitioning ratio and lattice misfit as well as rafting behavior and creep resistance at high temperature and low stress.

The experimental single-crystal superalloys containing different levels of Cr (0–5.7 wt.%) were investigated in the current study. The influence of Cr addition on microstructure and stress–rupture property at high temperature and low stress (1100 °C/140 MPa) has been investigated through changes in γ′ morphology, microstructural stability and elemental partitioning ratio as well as lattice misfit and rafting behavior in both dendrite core and interdendritic region. And the mechanisms by which Cr addition improve the stress–rupture property have been discussed.

2. Experimental procedures

Three experimental Ni-based single crystal superalloys with different levels of Cr addition (0–5.7 wt.%) were directionally solidified (DS) as single crystal bars (14 mm in diameter and 150 mm in length). Their compositions were determined by an atomic absorption spectroscope and are listed in Table 1. Alloy USTB-F1 is the baseline alloy without Cr addition. Alloys USTB-F2 and USTB-F3 contain intermediate level (2.8 wt.%) and high level (5.7 wt.%) of Cr, respectively. After solution treatment, thermal exposure tests were carried out at 1100 °C for different time. After the standard aging treatment (1140 °C/8 h + 870 °C/16 h), the specimens of the stress–rupture and creep tests were machined and the dimension of the gauge section was 5 mm in diameter and 25 mm in length. The stress–rupture testing was conducted at 1100 °C/140 MPa for three investigated alloys. Two specimens were tested for the same alloy. In order to investigate the effect of Cr addition on the tendency of the rafting behavior under the stress condition, the creep testing at 1100 °C was interrupted after the creep strain reached to 1% for three alloys. The maximum creep stress of 130 MPa was selected due to the limit of creep facilities. The stress–rupture and creep tests were conducted in the air.

Metallographic specimens for microstructural investigation were prepared and etched in a solution of 1% HF, 33% CH_3COOH, 33% HNO_3 and 33% H_2O. Microstructural observations were conducted using a ZEISS SUPRA 55 field-emission scanning electron microscope (FE-SEM) equipped with an energy-dispersive spectroscope (EDS). A back-scattered electron (BSE) detector was used to differentiate between the dendrite core and the interdendritic region.

In order to better describe the morphology of γ′ precipitates, the γ′ morphology was described as follows. γ′ precipitates were considered to be cuboidal and spherical if they were cubes and spheres, respectively. The intermediate shape was intervenient between cuboidal and spherical shape, and it has six planar γ/γ′ interfaces and eight rounded corners. The morphology between spherical and intermediate shape was defined as nearly spherical. And the morphology between intermediate and cuboidal was considered to be nearly cuboidal.

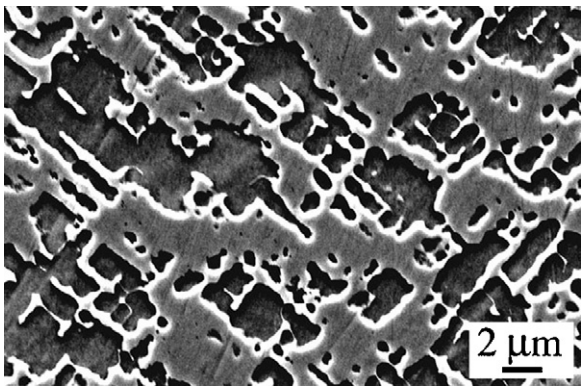

Fig. 1. Coarsened γ and γ′ phases in the dendrite core of alloy USTB-F3 after thermal exposure at 1100 °C for 800 h.

The volume fraction of γ′ precipitates was determined using the standard point count method. Measurement of the γ′ size and γ channel width was performed on SEM images using the Image-Pro software, an image analyzer program (see the web site: http://www.mediacy.com/index.aspx?page=IPP for more information). At least five images were used for determining the size and volume fraction of γ′ precipitates as well as the width of γ channels in each alloy. The degree of the rafting behavior after 1% creep stain was characterized by the linear termination density, ρ_l, which is represented by the following equation

$$\rho_l = \rho_a \cdot \lambda \tag{1}$$

where ρ_a is the average number of γ′ lamella terminations per unit area and λ is the thickness of the γ′ lamella [16]. The smaller the linear termination density, the more complete the rafting structure. Again, at least five SEM images were used for determining the linear termination density in each alloy.

The elemental partitioning ratio of γ and γ′ phases, k_i, is defined as

$$k_i = \frac{C_i^{\gamma}}{C_i^{\gamma'}} \tag{2}$$

where i represents each of the alloying elements, C_i^{γ} and $C_i^{\gamma'}$ correspond to the atomic concentration of element i in γ and γ′ phases, respectively. The partitioning ratio k_i greater or less than unity, indicates that the constituent element i preferentially partitioning to the γ or γ′ phase, respectively. Concentration profiles of γ and γ′ phases were measured by a JEOL JXA-8800R electron microprobe analyzer (EPMA) with four wavelength-dispersive spectrometers (WDS) under an acceleration voltage of 20 kV, a beam current of 20 nA and a spot size of 1 μm. Concentrations were obtained using a ZAF correction program, with pure element standards. In order to minimize the matrix effect, some γ and γ′ phases were apparently coarsened to at least 3 μm in size after thermal exposure at 1100 °C for 800 h, as shown in Fig. 1. All the EPMA analyses were carried out in polished but unetched samples. WDS spectra were collected from γ and γ′ phases in at least five areas for each experimental alloy. Values of C_i^{γ} and $C_i^{\gamma'}$ were averaged from above WDS analyses. Subsequently, lattice parameters of the γ and γ' phases were calculated by the formula presented by Ref. [17] according to their compositions. And then, the γ/γ′ lattice misfit (δ) is calculated as follows:

$$\delta = \frac{2(a_{\gamma'} - a_{\gamma})}{a_{\gamma'} + a_{\gamma}} \tag{3}$$

where a_{γ} and $a_{\gamma'}$ are the lattice parameters of the γ and γ′ phases, respectively.