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Effect of rhenium and ruthenium on the deformation and fracture mechanism in nickel-based model single crystal superalloys during the *in-situ* tensile at room temperature

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ABSTRACT

In-situ tensile experiments of Ni-Al, Ni-Al-Re and Ni-Al-Re-Ru model single-crystal superalloys were performed in scanning electron microscope (SEM) at room temperature. The plastic deformation mechanisms of all the three model superalloys were double-oriented slipping of dislocations. Micro-cracks were often formed at the intersection of two sets of slip lines. The fracture surfaces of Ni-Al and Ni-Al-Re-Ru alloys were nearly parallel to (010) planes and that of the Ni-Al-Re alloys was nearly parallel to (1−11) plane. The dislocation configuration was analyzed by transmission electron microscopy (TEM). The $a/2 < 110 >$ dislocation pairs coupled with antiphase boundary (APB) cut into γ′ phase in the Ni-Al and Ni-Al-Re-Ru model superalloys. In addition to these dislocations, stacking faults also cut into γ′ phase in Ni-Al-Re model superalloys. The different fracture surfaces of different model single-crystal superalloys were attributed to the influence of elements Re and Ru on the dislocation configuration.

1. Introduction

Nickel-based single crystal superalloys consist of cubical γ′ phases with $L1_2$ structure embedded coherently in γ matrix with a face-centered cubic structure. They have been widely used to manufacture advanced gas turbines because of their excellent creep and fatigue strength [1,2]. With the increasing demand of service performance, many different elements have been added into superalloys. As the second and the third generation symbolic element, rhenium (Re) has been found to reduce γ′ coarsening and significantly improve the creep property at high temperature [3–5]. However, an excess of Re decreases the creep strength by separation of hard, brittle topologically close-packed (TCP) phases [6,7]. The formation of TCP phases could be inhibited by adding ruthenium (Ru) [8]. Superalloys incorporating Ru are considered to be the fourth-generation superalloys with improved microstructural stability and creep resistance [9,10]. It is therefore important to understand the effect of Re and Ru on the microstructure and the microstructural evolution in the service process of nickel-based single crystal superalloys.

Fracture of superalloys often results from micro-crack generation and propagation. Investigating the effect of elements Re and Ru on the fracture process and microstructural evolution will increase our understanding of the role of each element. Most studies to date have concentrated on the generation location and propagation process of the micro-cracks. Micro-cracks are usually generated at the interfaces between the TCP phase and the γ matrix or the region of stress concentration interaction [11–13]. There are different opinions about the way crack propagation. Ott et al. posited that the cracks propagated along the γ channels or the γ/γ′-interfaces after rafting [14]. Tian *et al.* reported that cracks firstly propagated on the {001} and then along {111} planes during 760 °C/800 MPa creep process [12]. Feng et al. concluded that the crack mainly propagated along the TCP /γ′ interface [15]. Moverare et al. believed that crack propagation rapidly occurred along twinning planes during thermal−mechanical fatigue testing [13]. However, few researchers reported the effect of the alloying elements on micro-cracks generation and propagation. Further research on the effect of Re and Ru on the deformation and fracture mechanism of the superalloys is necessary.

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In this study, the plastic deformation and fracture behaviors of Ni-Al, Ni-Al-Re and Ni-Al-Re-Ru model single crystal superalloys were investigated by *in-situ* tensile experiments in SEM at room temperature. The dislocation configurations were analyzed using TEM. The purpose of these investigations was to understand the effect of Re and Ru on the plastic deformation and fracture mechanism of the superalloys.

2. Materials and experimental methods

Three types of Ni-based model single crystal superalloys were designed to study the effect of Re and Ru on the deformation and fracture mechanism. The chemical compositions (by wt%) of these alloys are listed in Table 1. The model superalloys were directionally solidified to form a [001] oriented single-crystal. A solution treatment was performed at 1330 °C for 20 h under flowing argon followed by water cooling, and an aging treatment was performed at 870 °C for 32 h followed by water cooling.

Table 1
Chemical compositions of three types model superalloys (wt%).

	Ni	Al	Re	Ru
Ni-Al	91.23	8.77	–	–
Ni-Al-Re	86.69	8.31	5.00	–
Ni-Al-Re-Ru	83.80	8.20	5.00	3.00

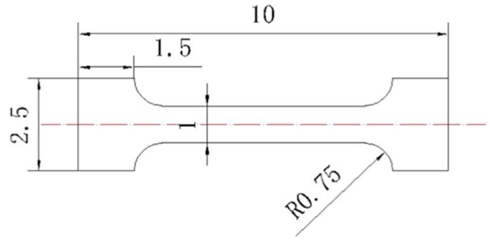

Fig. 1. The size of the tensile sample (mm).

The size of tensile sample was shown in Fig. 1. The samples for SEM were electrochemical etched using a solution of 40% nitric acid, 12% phosphoric acid and 48% vitriol (by volume fraction) at 5 V. The *in-situ* uniaxial tensile experiments were performed using a micro drawing mill, which was installed in SEM FEI Quanta250. The tensile axis was parallel to the [010] direction with a deviation angle less than 10 degrees. The experiments were performed at a constant strain rate of 1.4×10^{-4} s^{-1}. At least three samples for each type of model superalloys were stretched to minimize experimental errors. The samples for TEM were selected to be around 2 mm away from the fracture surface. The slices cut from samples were mechanically ground and polished to a thickness of 40 μm, and then the slices were thinned using a Gatan precision ion polisher system (PIPS) at 2–3 keV. TEM investigation was performed using JEM-2010F microscope operated at an accelerating voltage of 200 kV. The average size of γ' precipitates for three model superalloys was measured using the Adobe Photoshop and Image-Pro Plus software. At least five SEM images were measured for each sample to obtain accurate results.

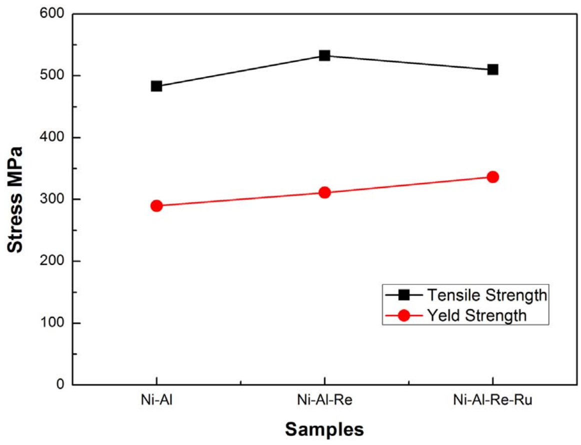

Fig. 3. The strength of Ni-Al, Ni-Al-Re and Ni-Al-Re-Ru model superalloys.

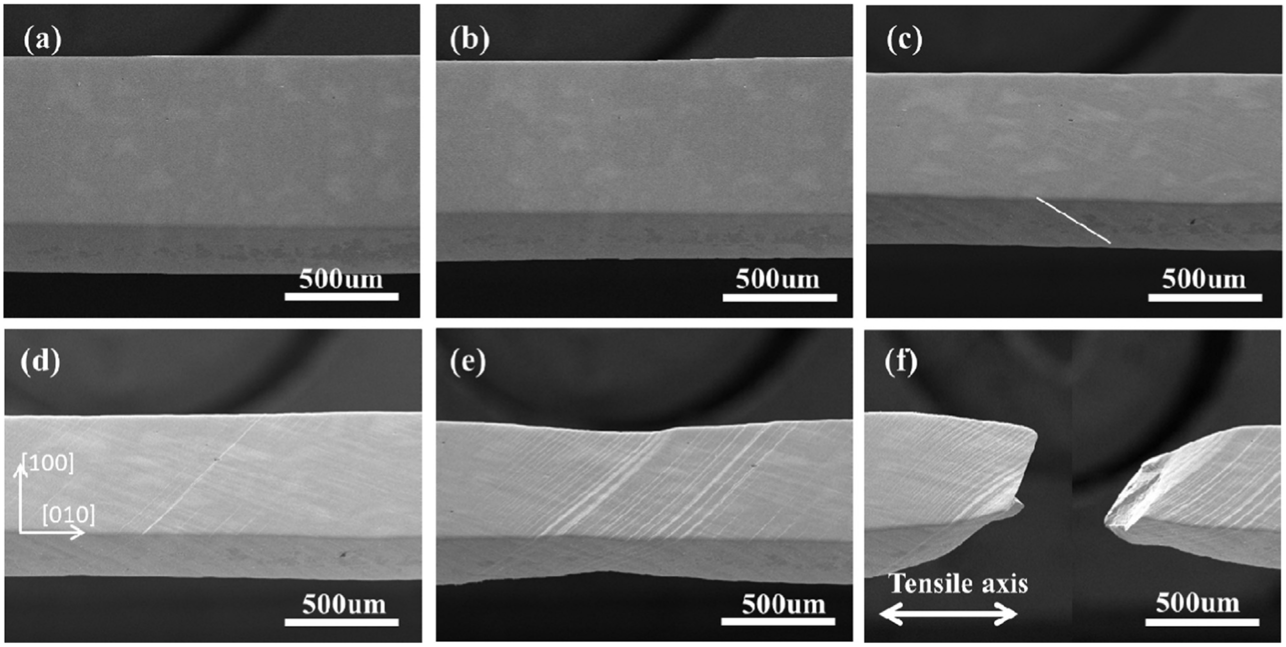

Fig. 2. *In- situ* tensile experiment process and fracture surface of the Ni-Al-Re model superalloy. (a) the initial state of the alloy. (b) the elastic stage of the alloy. (c) the appearance of first slip lines and the white line is the schematic slip line (d) second slip lines are activated. (e) necking propagation is induced by stress concentration. (f) fracture of alloy.

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