Effect of Ruthenium on Tensile Properties of a Single Crystal Ni-Based Superalloy

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The tensile properties of two single crystal Ni-based superalloys with and without added Ru (0 and 3 wt%) were investigated under a constant strain rate of 3.3×10⁻⁴/s at 20°C, 760°C, 800°C and 1000°C, respectively. The deformation mechanisms could be divided into two temperature regimes. From room temperature to 800°C, the deformation mechanism is caused by the shearing of γ' particles by anti-phase boundaries (APB) or stacking faults. At 1000°C, the deformation mechanism is caused by the bypassing of γ' particles by dislocations. At 20°C and 800°C, γ' particles were sheared by APB. Due to smaller γ' particles, the yield strength was decreased with addition of 3 wt% Ru. Additionally, work hardening is less pronounced in the alloy without Ru, hence the ultimate tensile strength was not decreased with the addition of 3 wt% Ru. At 760°C, γ' particles were sheared by stacking faults. Since the formation of stacking faults was promoted, the yield strength was decreased due to a 3 wt% Ru addition. However, the ultimate tensile strength was significantly increased when 3 wt% Ru was added. This is due to the markedly stronger work hardening caused by large numbers of stacking faults. At 1000°C, deformation occurred by dislocations bypassing γ' particles. Due to wider γ channels, the yield strength was decreased by 3 wt% Ru addition. Moreover, Alloy 3Ru has smaller γ' particles and a volume fraction as well as less pronounced work hardening, so the ultimate tensile strength was decreased when 3 wt% Ru was added.

Key words: alloys, solidification, strength, tensile test, microstructure

1. INTRODUCTION

As the current best candidate material for turbine blade and vane applications so far, single crystal Ni-based superalloys consist of high volume fractions of cuboidal L1₂ ordered γ' precipitates with a FCC disordered γ matrix. The continuous demand for enhancing the thrust-weight ratio and efficiency of aeroengines via a turbine entry temperature (TET) increase have pushed the development of single crystal Ni-based superalloys with improved elevated temperature properties. In an attempt to fulfill these requirements, increasing refractory elements, such as W, Re, Ta, Mo, etc., were added [1,2]. However, the precipitation of topologically close-packed (TCP) phases during prolonged exposure at elevated temperatures limits refractory element additions, especially Re [3,4]. In recent years, another significant alloying element, Ru, was chosen to solve this problem; it is evidenced that the high-temperature properties were indeed improved notably by Ru additions [5-8]. Thus, the effects of Ru on single crystal Ni-based superalloys have become the research focus.

In single crystal Ni-based superalloys, the main strengthening mechanisms include γ' precipitation strengthening and solid solution strengthening. Moreover, strengthening due to the presence of γ' involves coherency and order strengthening [1,2]. The strengthening phase, size, volume fraction and distribution of γ' particles play a key role in strengthening effects. It is well known that coherency strengthening is induced by a lower γ/γ' misfit (on the order of 10⁻⁵) and order strengthening acts when dislocation pairs cut through the γ' phase, leaving an anti-phase boundary (APB) inside them. Furthermore, the energy required to form an APB can impede cutting by dislocations, which in turn increases the strength of alloys [2]. Thus, it can be surmised that the alloy strength would depend on the integration of these strengthening effects.

The tensile properties of single crystal Ni-based superalloys with [001] orientation have been widely investigated, and generally present similar tensile behaviors.
temperature up to an intermediate temperature, the yield strength basically remains invariable or slightly increases with various strain rates. Then, it increases rapidly once it reaches an intermediate temperature. Beyond the intermediate temperature (700-800 °C), the yield strength decreases sharply and becomes strongly dependent on strain rates as temperature rises [9-12]. The ultimate tensile strength shows tendencies rather similar to yield strength [11,12]. Yeh and Tin [13] reported that the flow stresses of several single crystal Ni-based superalloys were increased by Ru additions at 900 °C and 1100 °C, since Ru additions appear to provide strengthening in both the γ and γ' phases. However, the Ru effects on tensile properties at low and intermediate temperatures were not involved in this study and the corresponding deformation microstructures were also not examined.

It is well established that, at low temperatures, the predominant deformation mechanism is the shearing of γ' particles by the α/2<110> dislocation pairs on {111} planes in connection with APB or stacking faults. When exceeding an intermediate temperature, deformation occurs when γ' particles are bypassed by single α/2<110> dislocations [10]. It is convincing that Ru additions would significantly affect the size of γ' particles, width of matrix channels, stacking fault energy, etc., thus influencing the tensile properties. In this study, the tensile properties of Ru-free and Ru-containing alloys from room to high temperatures were investigated. It aims at elucidating the effect of Ru on tensile behaviors at various temperatures.

2. EXPERIMENTAL PROCEDURES

Two single crystal Ni-based superalloys with and without Ru additions were designed to study the effect of Ru on tensile properties from room to high temperatures. The nominal chemical compositions of the alloys are listed in Table 1. According to their different Ru content, these two alloys are named 0Ru and 3Ru respectively. The master alloys were melted by vacuum induction and then directionally solidified into cylindrical bars (16 mm in diameter and 220 mm in length) in an investment casting cluster mold with a Bridgman furnace at a withdrawal rate of 6 mm/min. Conventional helical starters were utilized to initiate single crystal growth.

The single crystal bars were fully heat treated; for Alloy 0Ru, 1325 °C/8 h + 1335 °C/16 h air cooling (AC), 1150 °C/4 h AC, 870 °C/24 h AC and for Alloy 3Ru, 1315 °C/8 h + 1325 °C/16 h AC, 1150 °C/4 h AC, 870 °C/24 h AC. I-shaped test specimens, 2 mm thick and parallel lateral sides to (100) or (010) crystal planes, were machined by electro-sparking from the single crystal bars and solidified in an [001] axial orientation (as seen in Fig. 1). Tensile tests were performed with a Shimazu AZ-25KNE electronic tensile testing machine with a constant strain rate of 3.3×10⁻⁴/s at temperatures 20 °C, 760 °C, 800 °C and 1000 °C, respectively.

After tensile testing, the specimens were cut into discs of 500 μm thickness parallel to the lateral side, above 3 mm away from fracture and thinned down to 50 μm mechanically. They were then electrochemically polished with twin-jets, in a solution of 8% perchloric acid and 92% ethanol at −10 °C and 20-30 mA. A TECNAI 20 transmission electron microscope (TEM) was used to examine the dislocation configurations after tensile fracture. A JMS-6301F field-emission scanning electron microscope (SEM) was used to observe the fracture.

3. RESULTS AND DISCUSSION

3.1. Initial microstructure

Figure 2 shows the microstructures of both alloys after full heat treatment. The differences between Alloy's 0Ru and 3Ru γ' particles’ morphology could be observed clearly. Tan et al. [14] reported previously that the γ' size and volume fraction were decreased, γ' shape more regular and γ' particles distribution more uniform with 3 wt% Ru addition. The average size and volume fraction of the γ' particles and γ channels width are 0.51 μm, 73% and 42 nm for Alloy 0Ru, and 0.40 μm, 69% and 47 nm for Alloy 3Ru, respectively.