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Development of fine-grained structure in Ni-Cr-W based superalloy and its effect on the mechanical properties

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ABSTRACT

Ni-Cr-W based superalloys with different grain size have been prepared by specifically designed melt treatment technologies. The effect of grain refinement on the macrostructures, microstructures, morphology of precipitates, mechanical properties and the appearance of fracture in Ni-Cr-W based superalloy was investigated. The results showed that the grain refinement decreased the amounts of carbides and eutectics at the grain boundary, and made their distribution more uniform. Moreover, the above series of results changed the tensile fracture mode from transgranular to intergranular. The yield strength, tensile strength and elongation of Ni-Cr-W based superalloy are increased by grain refinement from room temperature (RT) to 900 °C, but this increase tendency gradually decreased with temperature increasing. In addition, an embedded serration was observed in stress-strain curve between 450 and 600 °C in Ni-Cr-W based superalloy. Compression tests were also conducted at RT, 550 and 900 °C, the stripe width of the compression specimen surface becomes small with grain refinement (from 10 μm to 5 μm). With the temperatures raising from room RT to 550 °C, the dislocation images of fine-grained specimen change from nanometer-scale dislocation lines to stacking faults.

1. Introduction

Due to excellent weldability properties and mechanical properties at high temperature, nickel-based superalloys are widely used for gas turbine components and other applications [1]. Nickel-based superalloys used in this condition require multi-step thermome-chanical processing (TMP). However, the conventional casting nickel-based superalloys are generally characterized by coarse and non-evenly cast microstructures, which do not provide the desired property combinations for TMP. Grain refinement has always been an important method to improve the mechanical performance of cast polycrystalline superalloys [2–5]. Generally, the effect of grain refinement on the cast superalloys consists of two aspects, one is the influence on precipitates [6] and the other one is the refinement in the microstructure [7,8]. Both the aspects would affect the mechanical properties of superalloys. Establishing the role of grain refinement on the microstructure and mechanical behavior of superalloys not only has a direct practical significance for improving the mechanical performance of engineering materials, but also helps in understanding the deformation mechanism.

The effect of grain refinement on the microstructure of superalloys have also been studied by other researchers. Sampath [9,10] found that the grain size of Cu-Zn-Al SMAs can be obviously reduced by Zr, Ti elements. Larson [11] have reported the effect of grain size on the creep property of IN792 superalloy at 704 °C and the results show that the increasing grain size can improve the resistance to creep crack growth. Morrison [12] investigated the effect of grain size on the room temperature (RT) fatigue crack initiation and showed that grain refinement significantly increases fatigue life, especially at low strain amplitude. Carbides are refined as grain refining, which was observed in superalloy by Liu [13] and Zhang [14].

It is noted that the studies mentioned above mainly focused on the microstructures and mechanical properties caused by grain refinement. However, the relationship among grain refinement, microstructure, precipitates and mechanical behavior between RT and 900 °C of Ni-Cr-W based superalloy is not studied systematically. There are still a series of unsolved problems, i.e. the mechanical property and the influence of temperature on the deformation behaviors are unclear in this superalloy, especially for the effect of different grain size prepared by specifically designed melt treatment technologies on mechanical property [15]. Therefore, the main issues on mechanical evolutions of this superalloy needs further investigations. In addition, Ni-Cr-W based superalloy is a solid-solution and carbide strengthened alloy, which is

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being explored in quest for excellent high temperature mechanical strength and long-term creep rupture strength used at about 1000 °C [16], hence, it is suitable to study on grain refinement. In this work, the effect of various microstructure under different conditions on mechanical properties are discussed, i.e., Ni-Cr-W based superalloy is chosen to evaluate the effect of grain refinement on the microstructure, precipitates, tensile behavior and deformation mechanism at RT, 450, 550, 600 and 900 °C.

2. Experimental materials and procedures

The chemical composition (wt%) of the alloy was: Cr, 19.82; W, 18.48; Mo, 1.24; Al, 0.46; C, 0.11; B, 0.0028; La, 0.026; P, S < 0.004, Bal. Ni. The liquidus and solidus temperatures of the alloy are 1400 and 1355 °C, respectively.

Grain refinement was achieved by being maintained near liquidus for appropriate time. About 30 kg of the alloy was heated to 1500 °C in Al_2O_3 crucible using the induction furnace and held at 1500 °C for 30 min. Subsequently, the melt was either maintained near liquidus (T_L=1400 °C) for 20 min before casting or directly poured into the mould, respectively. To compare the ingot obtained by being maintained and not being maintained near liquidus, microstructures of the samples casted with different conditions were characterized. Samples for microstructural and precipitated carbides observations were taken from the conventional (directly poured into the mould) and fine-grained ingot (being maintained near liquidus for 20 min before casting).

Microstructures of the samples casted with different processing conditions were characterized. Standard metallography procedures were followed in preparing the samples for examination. Careful surface preparation is mandatory as the signal comes from the top 50 nm of the surface. Therefore, the samples were ground on SiC abrasive papers down to a mesh size of 2000, followed by polishing with colloidal silica for a minimum of 1 h. The samples were then electro-polished using a mixture of 200 ml concentrated sulphuric acid and 800 ml methanol for 30 s. The grain distribution, microstructure, precipitates and appearance of fracture were observed using scanning electron microscope (SEM) at selected locations in the conventional and fine-grained ingot. The test bars were machined into standard tensile and compression specimens without heat treatment. The tensile and compression tests were conducted on the INSTRON 5582 testing machine and Gleeble3500 thermal simulator system, respectively. The tests were carried out with the protection of high purity argon (99.999%) , especially at low strain rates $10^{-3}s^{-1}$. Transmission electron microscopy (TEM) specimens were prepared from the fine-grained compressed specimen.

3. Results and discussions

3.1. Structure and carbides characterization

For macrostructural, microstructural and carbides analysis at various locations of column, column of 110 mm diameter×10 mm length was cut from the ingot (30 kg) of 110 mm diameter×290 mm length. The radial-transverse planes of the two ingots are shown in Fig. 1(a) and (b). Specimens were gotten along radial direction in the ingot, and macrostructures of the conventional casting and fine-grained casting are shown in Fig. 1(a) and (b), respectively.

Compared with fine-grained ingot, the microstructure of conventional ingot has dendritic primary and multiform equiaxed grains, as shown in Fig. 1(a). Meanwhile, there is relatively wide columnar grain zone in conventional ingot. Columnar grain has a certain orientation and grow along the direction of heat flow, and the average grain size of conventional ingot is 500 μm (size level is 2.15), as shown in Fig. 1(a). While microstructures of fine-grained ingot are only the globular and evenly equiaxed grains from the periphery to the center, and the

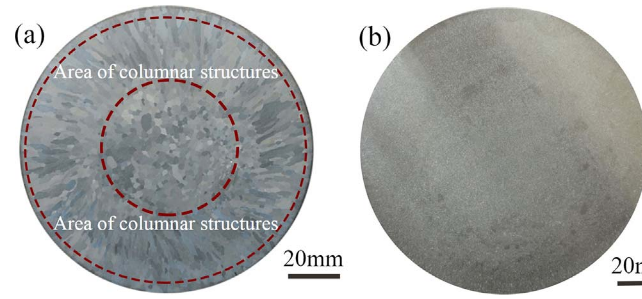

Fig. 1. Macrostructure of transverse section of 30 kg ingot in Ni-Cr-W based superalloy: (a) fine-grained ingot (b) conventional ingot.

average grain size is 300 μm (size level is 3.34), as shown in Fig. 1(b). Meanwhile, there is no columnar grain zone in fine-grained ingot. The grain size was measured by JEFFRIES method of Metal-methods for estimating the average grain size according to the National Standard of the PR China, GB/T6394-2004.

The effects of convection intensity level [17] and casting temperature [18] on grain refinement have been well documented in the literature. It is well known the important factors affecting on the microstructure are the treatment temperature near liquidus and electromagnetic field [19]. On the one hand, the forced convection of electromagnetic stirring could disperse inclusions, distribute them evenly and make phase fluctuation become much smaller in the melt, which can provide sufficient nucleation substrates and makes the melt temperature field becomes more evenly. On the other hand, there is a large number of evenly medium range order (MRO) in the melt when the melt is handled near liquidus [20]. The mechanisms of the grain refinement can be summarized as follows: during the melt holding at appropriate time in the transition state region, the melt temperature field becomes more evenly, which also makes phase fluctuation becomes small. This means that the quantities of clusters increase in the melt and the distribution of clusters is more evenly [21]. The formation of equiaxed and non-dendritic grains in ingots or castings near liquidus is believed to be due to the effect of clusters on nucleation [22]. Under a certain degree of undercooling, the size of the clusters reach the critical nucleation radius. In a word, equiaxed grains in castings can originate from both high nucleation derived from atom cluster and evenly solute field.

The mechanical properties of superalloys are affected seriously by carbides [23,24]. The role of different morphology of carbides in different grains is very complex. Hence, it is important to study carbides precipitation behavior and its influence on mechanical properties in different ingots. To determine the reinforcing mechanism of grain refinement, the typical morphologies of carbides analysis is adopted in Fig. 2.

The carbides are found to be regular rodlike in the interior of the grains and hexagonal shaped in both the interior grains and grain boundaries of fine-grained ingot, as can be seen from Fig. 2(a). The volume fraction of the carbides phase is about 10% in fine-grained ingot according to the calculation of Thermo-Calc software. Meanwhile, the morphology of carbides show dispersed distribution and most of the distribution around the grain boundary. The carbides are found to be regular bulk and dense distribution in both the interior grains and grain boundaries of conventional ingot, as can be seen from Fig. 2(b). The volume fraction of the carbides phase is about 18% in conventional ingot, which is higher than that of fine-grained ingot. Meanwhile, the morphology of carbides in conventional ingot show non-evenly distribution.

3.2. Tensile properties

To characterize the relationship between mechanical properties and their complex microstructures at different temperatures, effect of grain

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