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Influence of γ′ precipitate morphology on the creep property of a directionally solidified nickel-base superalloy

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Abstract

The effect of γ′ precipitates of different morphologies and sizes on the creep property of DZ951 alloy was investigated. Standard heat treatment (SHT) alloy has regularly aligned cubic γ′ phase and the γ′ size is about 300 nm. γ′ phase of HT1 alloy has the shape of cuboid and the size of 880 nm. HT2 alloy has γ′ precipitates of different morphologies and sizes. There is spherical γ′ phase of 150 nm in size between γ′ raftings. SHT and HT1 alloys have the same creep properties and small steady creep rates at 1040 °C/100 MPa, which is attributed to forming perfect rafting and regular dislocation networks in the γ/γ′ interface during creep test. The deformation structure of HT2 alloy is heterogeneous due to γ′ precipitates of different morphologies and sizes. It is easy for the dislocation networks to breakup because of high stress made by uneven deformation structure, which results in the short secondary stage and long tertiary stage at 1040 °C/100 MPa. SHT alloy is strengthened by tangling of dislocations each other without forming regular dislocation networks and perfect rafting structure at 850 °C/400 MPa, which results in high creep rate and short steady creep time. The low creep properties of HT1 and HT2 alloys arise from the heterogeneous deformation structure during creep test at 850 °C/400 MPa.

Keywords: DZ951 alloy; γ′ precipitate; Creep property; Dislocation

1. Introduction

Nickel-base superalloys are widely used in service conditions which require high strength at elevated temperatures. These materials have been specially employed for critical applications such as turbine blades of advanced military aircraft engines due to their high temperature strength, creep rupture strength and fatigue resistance. Their good mechanical properties at high temperatures are mainly related to the strengthening by the γ′ precipitates [1–4]. The morphology, size, volume fraction and distribution of γ′ phase have significant effect on the mechanical property of the alloy [5–12]. Caron and Khan [13] studied the effect of two heat treatments on the creep behavior of CMSX-2 superalloy and concluded that the heat treatment resulting in cuboidal aligned precipitates 0.45 μm in size led to a twofold improvement in creep lives over the corresponding values obtained with other heat treatment which produced smaller and more odd-shaped particles. Kakehi [14] investigated the effect of primary and secondary precipitates on creep strength of a nickel-base single crystal superalloy and concluded that the superfine secondary γ′ precipitate had a more significant effect on creep strength than the primary γ′ size. Nathal et al. [15] studied the effect of cuboidal γ′ precipitate and a continuous lamellar structure by a pre-rafting heat treatment on the intermediate temperature creep properties of a nickel-base single crystal. The results showed that the crystals with cuboidal γ′ precipitate had both lower minimum creep rates and longer rupture lives than the crystals with lamellar γ′ at high-applied stresses. At lower stresses, the cuboidal γ′ material indicated a low creep rate but exhibited a similar rupture life compared to the pre-rafted crystals. Therefore, γ′ morphology has significant effect on the creep property of superalloys. The purpose of this work is to investigate the influence of different morphologies of γ′ precipitates on the creep properties of DZ951 alloy.

2. Experimental

DZ951 alloy used in this work had the nominal composition (mass%): 0.05 C, 9.0 Cr, 5.0 Co, 6.0 Al, 3.0 W,

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3.0 Mo, 2.2 Nb, balance Ni. The alloy first was melted in VZM-25F vacuum induction furnace. The directionally solidified specimens of diameter 16 mm and length 220 mm were made by the method of high rate solidification (HRS) in ZGD2 vacuum furnace with a temperature gradient of 60–80 °C/cm and a withdrawal rate of 6 mm/min. The alloy was heat treated before creep rupture test. The procedure of standard heat treatment (SHT) was: 1220 °C/4 h,AC (air cooling)+1050 °C/4 h,AC + 870 °C/24 h,AC. SHT alloy was aged at 1000 °C and 1100 °C for 500 h and cooled in air to attain different γ′ morphologies. Specimens for creep rupture test with a gauge diameter of 8 mm and a gauge length of 50 mm were machined longitudinally from the heat-treated bars. Creep tests were performed using constant load lever arms at the conditions of 1040 °C/100 MPa and 850 °C/400 MPa. Temperature was measured with Pt–Rh thermocouples attached to the specimens gauge length. Creep strain was measured using extensometers attached to grooves in the specimen shoulders. Some tests were run to failure. Others were interrupted at various stages of creep and cooled under load to examine the structure.

Scanning electron microscope (SEM) and transmission electron microscope (TEM) were used to observe microstructure of DZ951 alloy. The SEM specimens were electrolyzed in a solution of 20 ml HNO_3 + 40 ml CH_3COOH + 340 ml H_2O with a voltage of 7 V. Cold field emission SEM was used to examine the γ′ phase. The TEM specimens were finally thinned by double-jet electrolyte machine in a solution of 30 ml $HClO_4$ + 270 ml CH_3CHO_2H at a temperature of −30 °C. The dislocation configuration was investigated by Philip EM420 TEM.

3. Results

3.1. The initial γ′ morphology

The shape of γ′ phase during different heat treatments is shown in Fig. 1. It demonstrates that the γ′ phase of SHT alloy has the shape of regularly aligned cuboid and the size of 300 nm. The distance between γ′ precipitates is about 30 nm. The γ′ size of the alloy after aging treatment at 1000 °C for 500 h (HT1) increases to 880 nm. The cubicity of γ′ phase is good. The matrix channel is about 100–150 nm. The alloy after aging treatment at 1100 °C for 500 h (HT2) has γ′ precipitates of different morphologies and sizes. γ′ phase coarsens rapidly for the big diffusion rate of atom at high aging temperature. The γ′ precipitates of large size can raft in the actions of elastic strain energy and interfacial energy. On the other hand, γ′ phase can dissolve again to matrix because of high aging temperature. Fine and spherical γ′ phase of 150 nm in size precipitates during followed cooling.

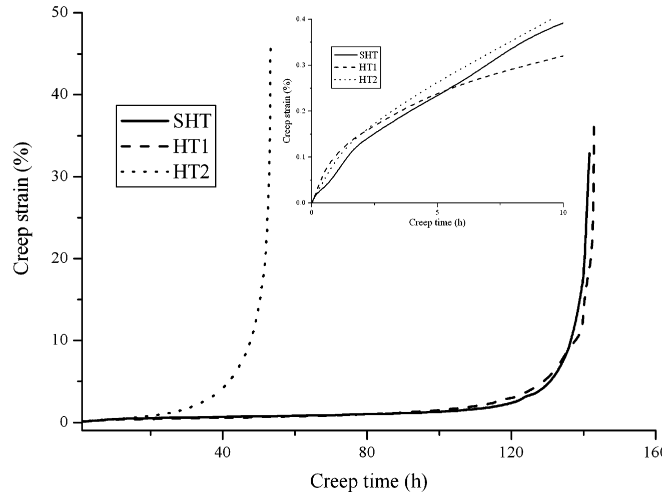

Fig. 2. Creep curves of the DZ951 alloy at 1040 °C/100 MPa.

3.2. Creep at 1040 °C/100 MPa

Fig. 2 shows the creep curve of DZ951 alloy at 1040 °C/100 MPa. The curves demonstrate obvious three creep stages. SHT and HT1 alloys have short primary and tertiary stage creep and long secondary stage creep. HT2 alloy has short secondary stage creep. Table 1 shows the creep property of DZ951 alloy. It indicates that the SHT alloy has the smallest steady creep rate. SH2 alloy has the smallest creep life.

The γ′ morphology of SHT alloy changes and some γ′ coarsens during primary creep at 1040 °C/100 MPa (Fig. 3a). Many dislocations move in the matrix and some ones bow in the γ′ interface (Fig. 3a arrow indicated). The experimental result of

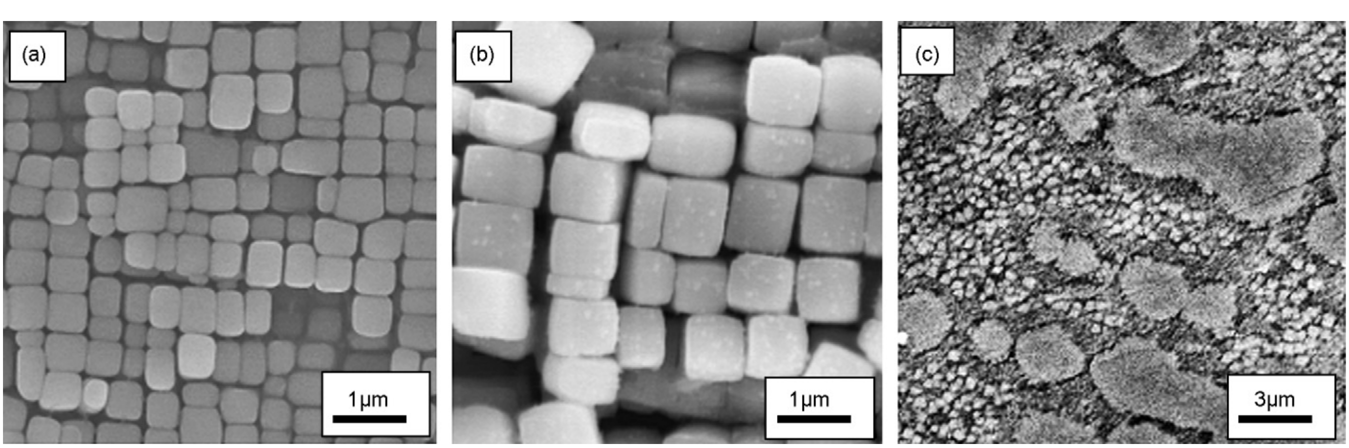

Fig. 1. The morphology of γ′ phase during different heat treatments: (a) SHT alloy, (b) HT1 alloy and (c)HT2 alloy.