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The influence of thermal exposure on the microstructure and stress rupture property of DZ951 nickel-base alloy

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Abstract

The effect of long-term exposure on the microstructure and the stress rupture property of a directionally solidified nickel-base superalloy was investigated. The results show that the MC carbide coarsens and the content of Nb in carbide increases with the rise of aging time. γ' size increases and γ' phase rafts with the rise of aging time at different aging temperatures. The driving force of rafting is the decrease of interface energy. There are bimodal γ' precipitates at the aging temperature of 1100 °C. The stress rupture life at 850 °C/420 MPa reduces with the rise of aging time during aging treatment, which is attributed to the γ' coarsening and the drop of γ' volume fraction. The fractographs at different conditions of aging treatments show ductile fracture mode. The fracture surface is related to the morphology and size of γ' precipitate.

Keywords: DZ951 alloy; Thermal exposure; Stress rupture property; Microstructure

1. Introduction

Nickel-base superalloys are widely used in manufacturing of gas turbine components which are required to possess high temperature strength, better oxidation and corrosion resistance, excellent fatigue and creep resistance, optimal stability of microstructure and service reliability [1,2]. Their good mechanical properties at high temperature are mainly related to the strengthening by the γ' precipitate [3–6]. It is well known that higher turbine inlet temperature may improve the efficiency of gas turbine engine. However, long-term service at such high temperature may cause changes in morphology, size, distribution and chemical composition of the γ' phase. The effect of long-term thermal exposure on the γ' phase and mechanical properties had been extensively investigated [7–16]. Stevens and Flewitt [16] investigated the effect of γ' precipitate coarsening during isothermal aging and creep property of a nickel-base superalloy IN-738. The result indicated that the γ' spheroid obeyed conventional $(\text{time})^{1/3}$ diffusion-controlled coarsening kinetics with an activation energy of 2.69×10^5 J/mol and coarsening of the γ' precipitates during isothermal aging was reflected by a decrease in room temperature hardness and an associated loss in creep resistance. Acharya and Fuchs [12] studied the effect of long-term thermal exposure on the microstructure and creep property of CMSX-10 single crystal nickel-base superalloy and concluded that the creep strength of CMSX-10 alloy during long-term aging degraded to be explained by the deleterious effect of γ' coarsening.

DZ951 directionally solidified nickel-base superalloy is mainly a vane material. It has the advantages of low density, low cost, high incipient melting temperature and better properties of thermal fatigue resistance and oxidation resistance. The better properties are attained by strengthening of γ' phase. It is essential for us to examine the stabilities of microstructure and property of DZ951 alloy during long-term service at high temperature. In this paper, the influence of long-term aging on the microstructure and the stress rupture property of DZ951 alloy is investigated.

2. Experimental

DZ951 alloy has the nominal composition (mass%): 0.05C, 9.0Cr, 5.0Co, 3.0 W, 3.0Mo, 6.0Al, 2.2Nb and balance Ni. The alloy first was melted in

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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 long-term thermal exposure. 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. Then the alloy was aged at 900, 1000 and 1100 °C for different times up to 2000 h and cooled in air. Specimens for stress rupture test with a gauge diameter of 5 mm and a gauge length of 25 mm were machined longitudinally from the aged bars. F-25 type stress rupture testing machine was used to test the stress rupture property of DZ951 alloy at the condition of 850 °C and 420 MPa at an ambient atmosphere. The stress rupture lives of DZ951 alloy were the average values of three specimens.

Scanning electron microscope (SEM) equipped with energy dispersive spectrometer (EDS) and transmission electron microscope (TEM) were used to observe microstructure of DZ951 alloy. 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. TEM specimens were prepared by twin-jet thinning electrolytically in a solution of 30 ml $HClO_4$ + 270 ml CH_3CH_2OH at −30 °C. The dislocation configuration was investigated by Philip EM420 TEM. Fracture surface observations were made on a Cambridge S360 SEM.

3. Results

3.1. Influence of thermal exposure on the microstructure of DZ951 alloy

Microstructure of SHT alloy consists of matrix γ, strengthening phase γ′ and MC carbide. The regularly aligned cuboidal γ′ phase has the size of 300 nm and the volume fraction of 68% (Fig. 2(a)). The MC carbide has the shape of block and EDS analysis indicates that it is rich in Nb and has the composition (mass%): Cr 4.98, Ni 18.65, Nb 53.43, Mo 13.82, W 2.06. Fig. 1 shows the change of carbide during different aging treatments. The morphology of carbide has slight change. The size of carbide increases with the rise of aging time at different aging temperatures. On the other hand, the carbide can dissolve at higher aging temperature. The volume fraction of MC carbide drops to 0.72% compared to 1.17% at SHT alloy when the alloy is aging treated at 1100 °C for 1000 h. The carbide composition has significant change. EDS analysis indicates that the content of Nb in MC carbide increases with the rise of aging time during different aging treatments. The MC carbide during aging treatment at 900 °C for 2000 h has the composition (mass%): Cr 4.34, Ni 24.56, Nb 69.94, W 1.16. The content of Nb continues to go up with the increased aging temperature. Finally, MC carbide changes completely into NbC during aging treatment at 1100 °C for 1000 h.

The change of γ′ phase at the aging temperature of 900 °C is shown in Fig. 2. The γ′ size at 900 °C for 100 h slightly increases. Small γ′ precipitates gradually dissolve and large γ′ ones coarsen and raft with the rise of aging time. The volume fraction of γ′ phase reduces to 64% at the aging time of 2000 h. The γ′ size at the aging temperature of 1000 °C increases with the rise of time (Fig. 3). The cuboidal γ′ phase is more regular than that at 900 °C. The γ′ volume fraction further drops to 62% at the aging time of 2000 h. There are some fine and spherical γ′ precipitates at the aging temperature of 1100 °C (Fig. 4). The coarsening of γ′ phase is very obvious. Many γ′ precipitates raft.

3.2. Influence of thermal exposure on the stress rupture property of DZ951 alloy

Fig. 5 shows the stress rupture lives of alloys during different aging treatments at 850 °C/420 MPa. The stress rupture life drops at higher aging temperature. The longer the aging time, the lower the stress rupture life. It is interesting to note that there are longer stress rupture lives during aging treatment at 1000 °C from 1000 to 2000 h than that at 900 °C, which is related to the γ′ rafting.

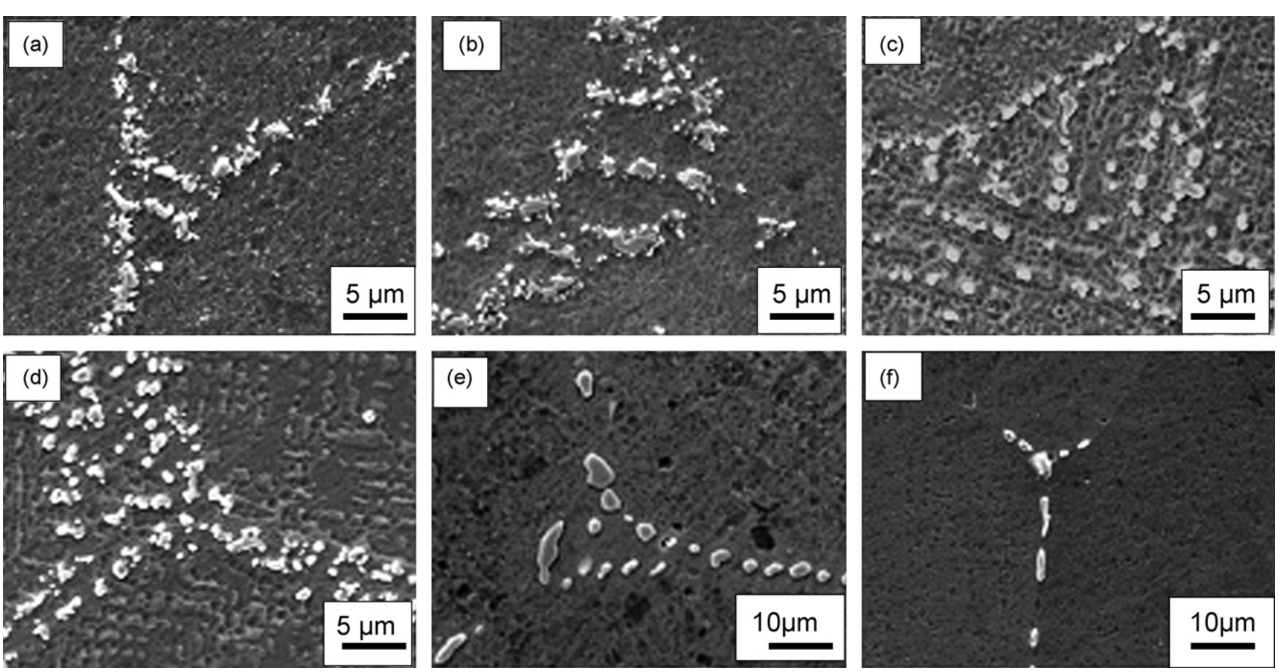

Fig. 1. The change of MC carbide at 900 °C for (a) 100 h and (b) 2000 h; at 1000 °C for (c) 500 h and (d) 2000 h; at 1100 °C for (e) 500 h and (f) 1000 h.