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Study on Stress Rupture Properties of an Advanced Wrought Nickel-Based Superalloy Based on Microstructure Characteristics

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Abstract. Stress rupture experiments were performed on GH4151 nickel-based superalloy specimens. The microstructure analysis, fracture morphology analysis, and dislocation structure analysis were carried out. The results indicate that the life of the alloy decreased significantly with increasing temperature and stress. Furthermore, the microstructure evolution during stress rupture deformation was dislocation formed in γ channel, dislocation network, dislocation shearing into γ' phases and stacking faults forming, extended stacking fault, and rafting γ' phases. In high temperature, grain boundaries are easier to slide, dislocations are easy to accumulate during deformation, and the dislocations cut the γ' phase and thus the strengthening effect is weakened, which makes the crack initiation and propagation earlier and the life of the alloy shorter. In addition, with the increasing stress, the enhancement of dislocation density and the rafting of γ' phases becomes more obvious, which decrease strength of alloy and stress rupture life.

Keywords. GH4151, superalloy, microstructure, stress rupture, mechanism

1. Introduction

Owing to their moderate strength and excellent structure stability, nickel superalloys have been used in aircraft, and other fields [1–8]. The efficiency requirement of aero engine requires the increase of service temperature [9], which requires excellent performance of the superalloy. GH4151 alloy is a novel Ni-based superalloy strengthened by γ' phase precipitation. Its γ' phase precipitation volume fraction is around 52%, which can be used in turbine disk manufacturing at 750 °C and above.

High stress fracture performance is the prerequisite and basis for the alloy to be able to exhibit predictable and minimal time-dependent deformation to ensure a small gap between rotating blade tips and housing to improve engine efficiency. In addition, the stress fracture damage of the superalloy has a great influence on the safety of the disk [10]. Therefore, the study of high temperature stress fracture behavior and stress

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fracture performance of alloy will provide a basis for the safe use of alloy and the expected life of disk.

For example, Maclachlan, D.W. studied that the addition of Ru significantly improves the stress-rupture life due to higher γ 'volume fraction, more negative lattice mismatch and good drift structure, as well as smaller γ channel widths [11].

Xie et al. studied the interaction between γ 'phase and dislocation at 650 ~ 670°C, and analyzed the deformation mechanism of the alloy [12]. The creep mechanism of the superalloy containing 6wt% Re and 5wt% Ru were studied via microstructure observation by Zhao Guoqi [13]. Tian Chenggang studied the deformation microstructure of two nickel-based superalloys with different Co contents after creep at different conditions [14]. Cui Jinyan [15] was used to study the influence of these microstructure evolution on the stress-fracture properties of WZ-D2 alloy.

However, the study of single superalloys were mainly focused on, the investigation of cast and deformed superalloys was less. In this project, the microstructure transformation and different stress fracture mechanisms of the alloy were studied by applying different conditions. The results provide a basis for the development of the GH4151 alloy.

2. Material and Methods

The ingot was gotten by vacuum induction smelting (VIM) and electroslag re-smelting (ESR). The main chemistry composition of GH4151 alloy is list in table 1.

Table 1. The main composition of test material (mass percent %).

Al	Cr	Mo	Ti	V	C	Nb	W	Ce	Ni
3.7	11.9	4.5	2.8	0.5	0.06	3.4	2.7	trace	Bal

A GH4151 superalloy disc was employed as experimental material to prepare stress rupture samples. The samples were stress rupture tested at two different conditions: 750°C/500MPa, 800°C/500MPa and 750°C/650MPa. The micro-structures evolution were implemented by the optical microscope, the scanning electron microscope, and the transmission electron microscope.

For the optical microscope, the specimens were prepared through H_3PO_4 (150ml) + Cr_2O_3(15g)+ H_2SO_4 (10ml). For the scanning electron microscope observation, the specimens were prepared by etching electrolytically at 3-4V in an aqueous solution of 10% phosphoric acid. The specimens were gotten by several thin disks with the thickness of 50 μm and a diameter of 3 mm, and then double-jet eletropolished using a solution of 95% alcohol and 5% perchloric acidat 35 V. TECANI G2 operated at 200 kV was used to study the microstructural features.

3. Results

3.1. Stress Rupture Behavior of Disk

Sampling along the chord direction of the disc was taken to test the rupture behavior of the GH4151 (see in table 2). The data show that with increasing stress and temperature, the life of GH4151 decreases. In addition, the elongation and shrinkage increase with the increasing temperature and stress.

Table 2. Rupture data of GH4151 disk.

Temperature/°C	Stress/MPa	Time/h:min	Average time/h	Elongation δ/%	Average δ/%
700	500	321:10 335:50	328.5	14.52 17.72	16.12
	650	111:30 96:30	104	10.04 9.96	10.00
800	500	32:20 34:40	33.5	20.24 30.72	25.48

3.2. Effect of Temperature on Microstructure after Stress Rupture Test

The fracture morphology observations were conducted on this new Ni-based alloy at 700 °C/500MPa and 800 °C/500MPa for stress rupture testing, as shown in figure 1. The fracture surface at 700 °C/500MPa shows brittle fracture characteristics, as shown in figure 1(a). At high magnification, the grain boundary crack characteristics are not obvious, as shown in figures 1(b) and (c). However, at 800 °C/500MPa, the fracture surface shows good plastic characteristics, and the dimple phenomenon is obvious, as shown in figures 1(e) and (f). In addition, it can be seen that the surface layer is intergranular fracture morphology, and cracks occur on the grain boundary and propagate along the grain boundary.

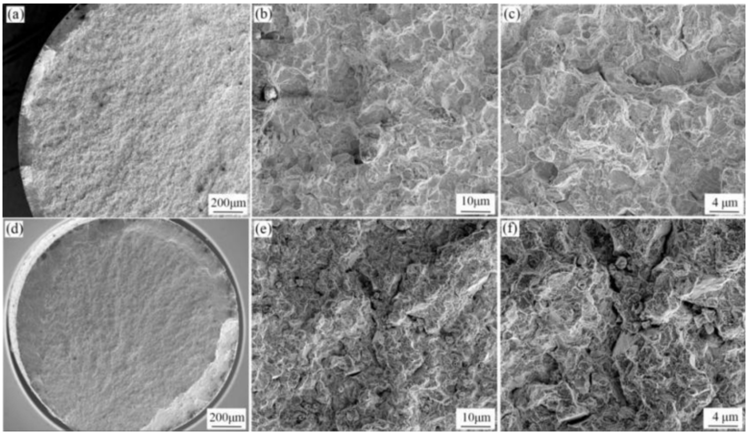

Figure 1. Fracture morphology of stress rupture specimens (a)(b)(c), 700 °C/500MPa and (d)(e)(f), 800 °C/500MPa.

The dislocations near the fracture surface were examined by means of TEM under 700 °C/500MPa and 800 °C/500MPa, as shown in figure 2. At 700 °C/500MPa, thin strips of stacking faults appear in the microstructure (figure 2(a)), dislocations are distributed regularly in γ channel (figure 2(b)), and there exit stacking faults in γ' phase (figure 2(c)). At 800 °C/500MPa, thin strips of stacking faults are more in low magnification (figure 2(d)), and dislocations in γ channel are arranged more complex and their density increases (figure 2(e)), while stacking faults in γ 'phase decrease and dislocations by passing γ 'phase increase (figure 2(f)).

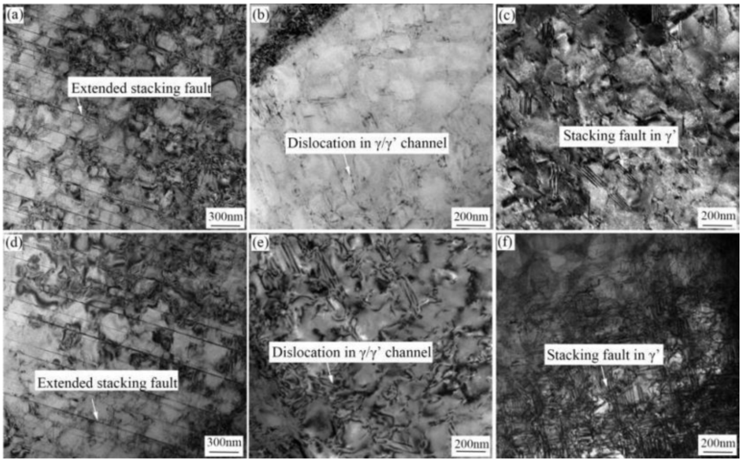

Figure 2. TEM images near surface of specimens (a)(b)(c), 700 °C/500MPa and (d)(e)(f), 800 °C/500MPa.

3.3. Effect of Stress on Microstructure after Stress Rupture Test

The data in the table 2 indicates that the stress rupture lifetime reduced more obviously with increasing stress. At the same test temperature of 700 °C, it reduced from 328.5 h to 104 h as the increasing stress from 500 MPa~650 MPa, which decreased by 68.3%. Moreover, the elongation rate reduced from 16.12 % to 10.00 % as the increasing stress from 500 MPa ~ 650 MPa, which dropped by 38.0%. It is obvious that rupture property of the GH 4151 is sensitive to stress.

Figure 3 suggests the rupture fracture morphology of the experimental GH4151 at 700 °C/500MPa and 700 °C/650MPa. At 700 °C/500MPa, there are local dimples in fracture morphology, showing plastic characteristics; At 700 °C/650MPa, the specimen shows quasi-cleavage morphology, which is brittle characteristics.

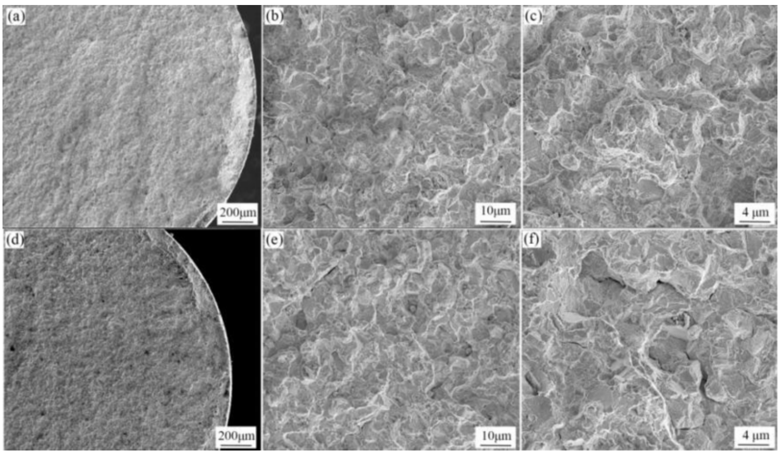

Figure 3. Fracture morphology of stress rupture specimens (a)(b)(c), 700 °C/500MPa and (d)(e)(f), 700 °C/650MPa.

The dislocation morphology of stress rupture specimens under different stresses is similar to the above-mentioned morphology, as shown in figure 4. At the initial stage of persistent deformation, dislocations of integral cutting γ and γ 'phases are produced (figure 4(a)), and under high stress, the dislocation density of integral cutting two phases is higher (figure 4(d)). On the other hand, few dislocations are exited in the matrix, and many dislocations are generated and propagated in the γ channel (figure 4(b)). With the further deformation, the strain increases, and dislocations begin to accumulate at the interface between the two phases, which makes the movement of dislocations gradually difficult. Further deformation, for high stress specimens, the dislocation slip ratio enhances, the dislocation density of γ channel enhances, the γ' phase was cut by the slip dislocations and decompose as stacking faults, as shown in figure 4(c). For high stress specimens, more dislocations will accumulate at the grain boundary and γ/γ' interface (figures 4(e) and (f)), resulting in stress concentration, thus reducing the stress rupture life.

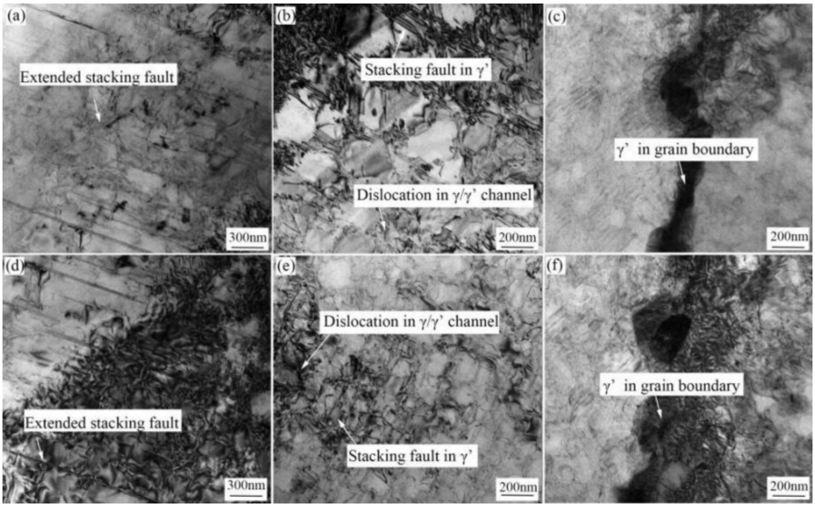

Figure 4. Dislocation morphology of stress rupture specimen (a)(b)(c), 700 ℃/500MPa and (d)(e)(f), 700 ℃/650MPa.

4. Discussion

To summarize the descriptions, a conceptual model for the deformation mechanisms in after stress rupture test is proposed, and is shown in figure 5.

At the primary stage of the stress rupture, as shown in figure 5(a), many dislocations rapidly form and multiply in the γ phase. As the elastic deformation, under the joint action of external stress and γ'/γ mismatch, these dislocations are continuously emitted from γ matrix channel, and form the γ' /γ interface dislocation network stacked in front of γ 'phase through dislocation reaction, as seen in figure 5(b). Regular dislocation morphology in γ channels perform an important effect in properties of superalloy [16]. These dislocation networks will prevent dislocations in matrix channels. However, with the deformation proceeding, some of the dislocations in the γ phase cut into the γ' as the stacking faults (SF), contributing to a morphology of stacking fault. In the alloy with low dislocation energy, some dislocation penetrates the γ matrix and γ 'phase to form extended dislocation (see figure 5(c)). During the last process, directional drift of γ'phase occurred under the combined action of external stress load and temperature, as described in figure 5(e).

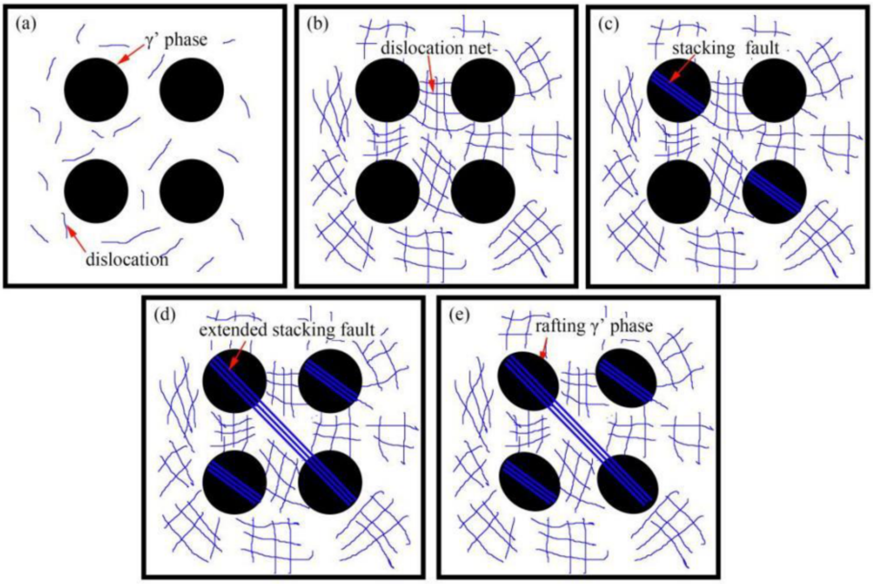

Figure 5. The conceptual model for the deformation mechanisms in after stress rupture test.

Increasing temperature will activate movement of dislocations, that is, the increasing temperature will increase the dislocations densities [16]. At 700 ℃/500MPa, the grain boundary strength is high, and the fracture presents transgranular fracture characteristics, as shown in figure 1. Compared with high temperature, the microstructure of the sample will undergo more intragranular deformation, which reduces the stress concentration at grain boundaries and makes the deformation more uniform. Therefore, the chance of crack initiation is less, and finally the stress rupture life of 700 ℃/500MPa is longer. The fracture surface at 800 ℃/500MPa shows good plastic characteristics, and dimple phenomenon is obvious. The fracture surface at high magnification shows intergranular fracture morphology, and cracks occur along the grain boundary and propagate along the boundary. For high temperature environment, it is easier for grain boundaries to slide. Due to the sliding, more dislocations will be generated at grain boundaries, and dislocations are easy to accumulate during deformation. For the deformation in γ', the slip dislocations pitch into γ' phase through γ/γ' interface, and the cut-in dislocations decompose into stacking faults. The stress concentration is more obvious at high temperature, and the dislocations cut the γ' phase, and then the dislocation morphology is decomposed into a higher proportion, as shown in figures 4(c) and (f). The effect of γ 'phase strengthening was weakened, which makes the crack initiation and propagation earlier and the life of the alloy shorter.

The stress promotes the dislocation motion increases accordingly and the dislocations of the alloy move faster under higher stress. When the applied stress changed from 500 MPa to 650 MPa, the dislocation density of the specimen increased further and a more dense γ'/γ interface dislocation network was formed Slip dislocations sheared into the γ' phases and left the stacking fault. With the increasing applied stress, antiordered strengthening and the interaction strengthening between dislocations, stacking faults in γ' phases occur more in the alloy Therefore, with the increase of stress, the increase of dislocation density and the rafting of γ' phases becomes more obvious, which decrease strength of alloy and stress rupture life.

The dislocation motion is increased by stress, and the dislocation motion is faster at higher stress. When the applied stress increases from 500 MPa~650 MPa, the dislocation density of the sample further increases (see figures 4(a) and (d)), forming a denser γ'/γ interface dislocation network (see figures 4(c) and (f)). Slip dislocations cut into the γ' phase and form stack faults. The lamination of γ 'phase increases with the increase of applied stress, the strengthening of dislocation sequence and the strengthening of dislocation interaction (see figures 4(b) and (e)). Therefore, with the increasing stress, dislocation density increases and γ' phase drift becomes more obvious, which decrease strength of alloy and stress rupture life.

5. Conclusions

The stress rupture behavior have been investigated for GH4151 alloy. The following results are the main conclusion:

1) With increasing temperature and stress, the stress rupture life of the alloy decreases. In addition, the elongation and shrinkage of section increase with the increasing temperature and stress.

2) The fraction of transgranular fracture is the majority in the fracture surface at 700 °C/500MPa, and intergranular fracture is the main feature at 800 °C/500MPa. In high temperature, grain boundaries are easier to slide, dislocations are easy to accumulate during deformation, and the dislocations cut the γ' strengthened phase and the effect of γ' phase is less, which makes the crack initiation and propagation earlier and the life of the alloy shorter.

3) At 700 °C/650MPa, there are local dimples in fracture morphology, showing plastic characteristics; At 700 °C/650MPa, the specimen shows quasi-cleavage morphology, which is brittle characteristics. As the increasing stress, increase of dislocation density and the rafting of γ' phases becomes more obvious, which decrease strength of alloy and stress rupture life.

4) The microstructure evolution during stress rupture deformation was dislocation formed in γ channel, dislocation network, dislocation shearing into γ' phases and stacking faults forming, extended stacking fault, and rafting γ' phases.

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