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Influence of Grain Size on Tensile and Stress Rupture Behavior of an Advanced Wrought Ni-Based Superalloy

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Abstract. In this study, the tensile and stress rupture behavior were investigated on GH4151 alloy with different grain sizes. The test samples were obtained from turbine disk with different positions. The analysis of micro-structure, grain size, and fracture morphology were carried out by several typical characteristics way, indicating that the influence of grain size on tensile and stress rupture behavior is mainly affected by the number of grain boundary, which affects tensile and stress rupture behavior of the GH4151 superalloy. The tensile strength of fine-grained specimens are higher than tensile strength of coarse-grained specimens, and so is the plasticity. At the same test condition, stress rupture life reduced from 82.5 h to 33.5 h as the grain size decreased from 22.3 μm to 11.1 μm, which decreased by 59.4%. Moreover, the elongation rate increased from 6.60 % to 25.48 % as the grain size decreased, which increased by 286%.

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

1. Introduction

Nickel superalloys have been used in aircraft, energy, and other fields contributing to their good comprehensive properties and high temperature resistance [1–8]. The high efficiency of aero-engine requires higher intake temperature and higher efficiency of turbine [9], which requires superalloy to have excellent thermal and mechanical properties. GH4151 alloy is a new nickel-based wrought superalloy strengthened by γ'phase precipitation. Its γ' phase precipitation volume fraction is about 52%, which can be used in turbine disk manufacturing at 750 °C and above. For improving the high temperature comprehensive properties of GH4151 alloy, the optimum composition of GH4151 alloy with Nb content of 3.4% and total Al, Ti and Nb content of about 10% was designed.

The coarse grain size of wrought superalloys is one of the key factors causing the degradation of alloy properties and application level. Fine grain is good to the benefit of improving the comprehensive properties [10-18], which is a good means to increase the service life of castings. Therefore, the influence of refined grain on the

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comprehensive properties is related to the test environment, and the influence of grain size on the mechanical behavior of superalloys has always been a research hotspot. The influence of grain size on the creep properties of the alloy was studied [19], and it was found that the creep properties of IN792 alloy increased with the increasing grain size from 650 °C to 760 °C. The creep behavior of nickel-based superalloy NR6 with different grain sizes at 700 °C/700 MPa [20]. It can be seen that coarse grain sizes increase the inhomogeneity of intragranular creep deformation, but decrease the inhomogeneity of grain boundary creep deformation, and lead to slip hysteresis of grain boundary. Researchers [21] analyzed the relationship between grain refinement and room temperature strength of IN713-LC cast superalloy, and thought that with grain refinement, the room temperature yield strength of the alloy gradually enhanced.

Although there are many investigation on the relationship between grain size and mechanical properties of superalloy, most of them are about the influence of refined grain on deformation mechanism of cast superalloys. The research on wrought alloys is not exhaustive, therefore, the tensile properties and stress rupture properties of GH4151 wrought superalloy with different grain sizes are studied in this work. The results will provide help and theory basis for the engineering application of GH4151 alloy.

2. Material and Methods

The electrode was prepared by vacuum induction melting. After casting, the electrode is polished and trimmed, and its size is Φ280mm*1790mm. The electrode needs to be baked at 350℃* 2h before esR remelting. Finally, electroslag ingot was prepared. The main chemical constituents of GH4151 alloy are shown in table 1. After homogenization, extrusion, die forging and final heat treatment, the disk material for test was obtained. Tensile and stress fracture specimens were prepared using GH4151 alloy disk as raw material.

Table 1. Chemical 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

The two experiments were taken from different positions of the disk, and there were different grain sizes due to different strain. However, due to the same solution + aging heat treatment, the precipitated phase types were the same, so it can be used to study the influence of grain sizes on stress fracture and tensile behavior.

The microstructure evolution was implemented by transmission electron microscope (TEM), scanning electron microscope (SEM), optical microscope (OM), and energy dispersive spectroscopy (EDS).

The SEM and OM samples were prepared by 10% phosphoric acid solution and 3-4V electrolytic etching in Cr_2O_3(15g) + H_3PO_4 (150ml) + H_2SO_4 (10ml) solution, respectively. The microstructure was observed by Leica DM6000M optical microscope and Quanta 200FEG. In TEM analysis, the sample was prepared from several thin slices with thickness of 50 μm and diameters of 3 mm and then double-jet electropolishing was performed with a solution of 95% ethanoland 5% perchloric acid at 40 V. The microstructure characteristics of polished samples were studied by using 200 kV TECANI G2 transmission electron microscope.

3. Results

3.1. Influence of Grain Size on Tensile Behavior

The microstructure of GH4151before tensile tests was observed by SEM and OM, and the results are exhibited in figure 1. The two samples are equiaxed crystals, as seen in figures 1(b) and (e). Using the cross-section-method, the grain sizes for the two samples are 82.3 μm and 12.1 μm, respectively. The distribution of MC carbides and γ' phase in the two samples is similar after the same solution and aging heat treatment. MC carbides and γ' structures were randomly distributed in grains and at grain boundaries, as described in figures 1(a), (c), (d) and (f).

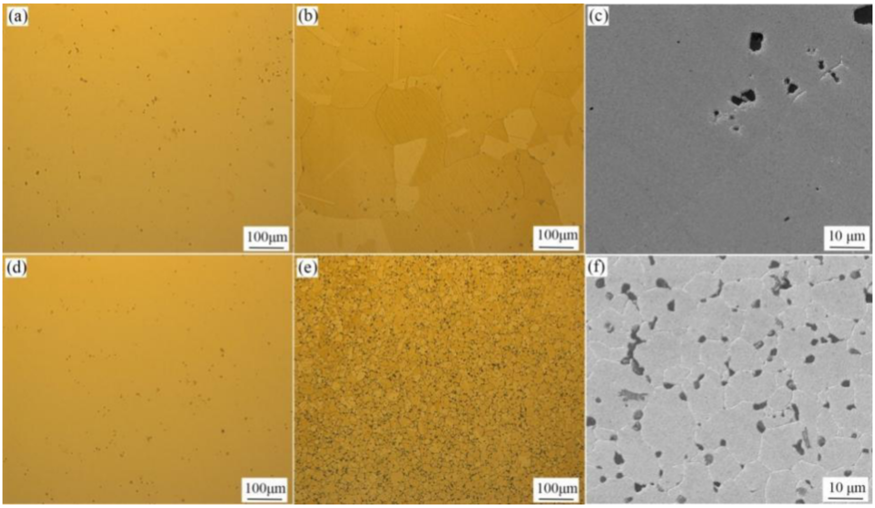

Figure 1. The MC, grain, and γ’ phase microstructure of specimens. (a)-(c) Coarse-grain specimen; (d)-(f) Fine-grain specimen.

Sampling along the chord direction of the disc was taken to test tensile properties of GH4151 alloy. Table 2 exhibits the test results of tensile behavior of samples with different grain sizes. The fine-grained tensile strength at room temperature is higher than strength of coarse-grained specimens, and so is the plasticity. It can be found from the fracture surface that coarse-grained specimens have obvious brittle fracture characteristics (see in figures 2(a), (b), and (c)), while fine-grained specimens have dimples characteristics (see in figures 2(d), (e), and (f)). The fraction of transgranular fracture is the majority in the fracture surface within coarse-grain specimen, as shown in figures 3(a) and (b), and intergranular fracture is the main feature at within fine-grain specimen, as shown in figures 3(d) and (e). Figures 3(c) and (f) show that the distribution characteristics of γ'phase under the two conditions are consistent.

Table 2. The tensile properties of coarse-grained and fine-grained specimen.

	σ_b/Mpa	**$\sigma_{p0.2}$/MPa**	**δ_5/%**	**Ψ/%**
Coarse-grain specimen	1433	1091	12.0	13.9
Fine-grain specimen	1701	1309	16.9	17.2

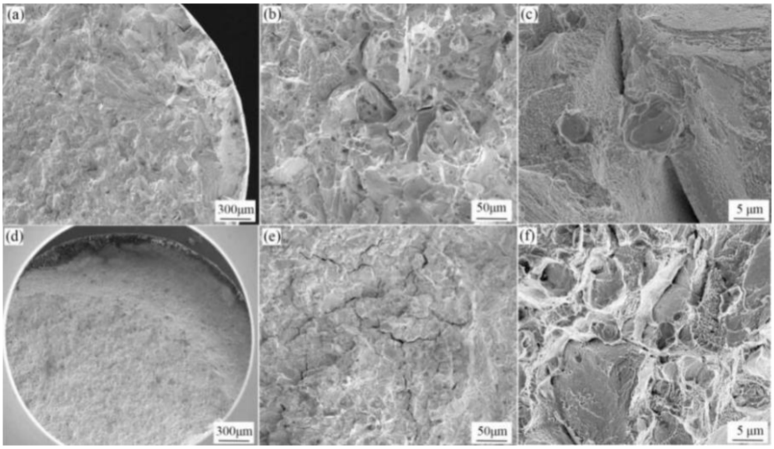

Figure 2. Fracture morphology. (a)-(c) Coarse-grain specimen; (d)-(f) Fine-grain specimen.

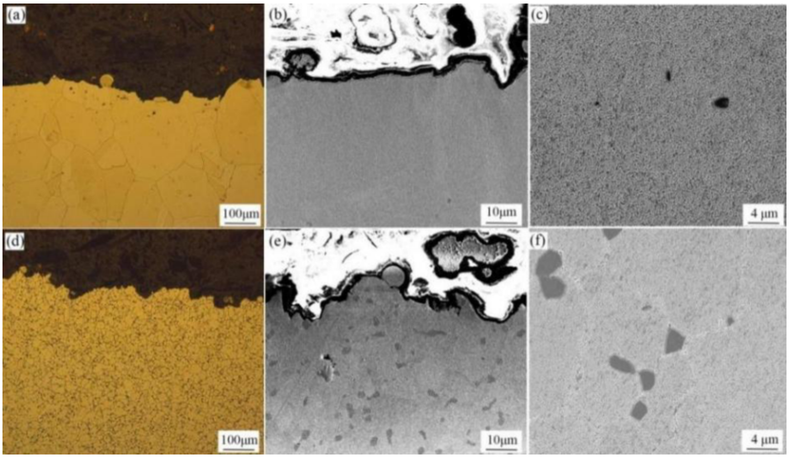

Figure 3. Microstructure and fracture side microstructure. (a)-(c) Coarse-grain specimen; (d)-(f) Fine-grain specimen.

It is considered that the improvement of tensile strength is related to fine grain strengthening. The grain size is small, while the grain boundaries increase and obstacles increase, which requires a large external force to make the crystal slip [22]. Therefore, the yield strength of materials with fine grains increases. Because of the different orientations of two grains, the movement direction of dislocation must be changed when moving from one grain to another and the mismatch between two grains will seriously hinder the movement of dislocation. Therefore, the smaller the grain size, the stress distribution is more uniform when the alloy undergoes plastic deformation, which delays the generation of cracks, so the plasticity increases.

3.2. Effect of Grain Size on Stress Rupture Properties

The micro-structure of GH4151disc was observed by two characteristics methods. The results are shown in figure 4. Both samples are composed of equiaxed grains, as seen in figure 4. According to cross-section method, the average grain sizes of the two samples are 22.3 µm and 11.1 µm, respectively. Combined with precipitation and redissolution law of precipitated phase, γ’ phase distribution of the two samples is similar after the same solution + aging heat treatment, as shown in figures 4(b)-(f).

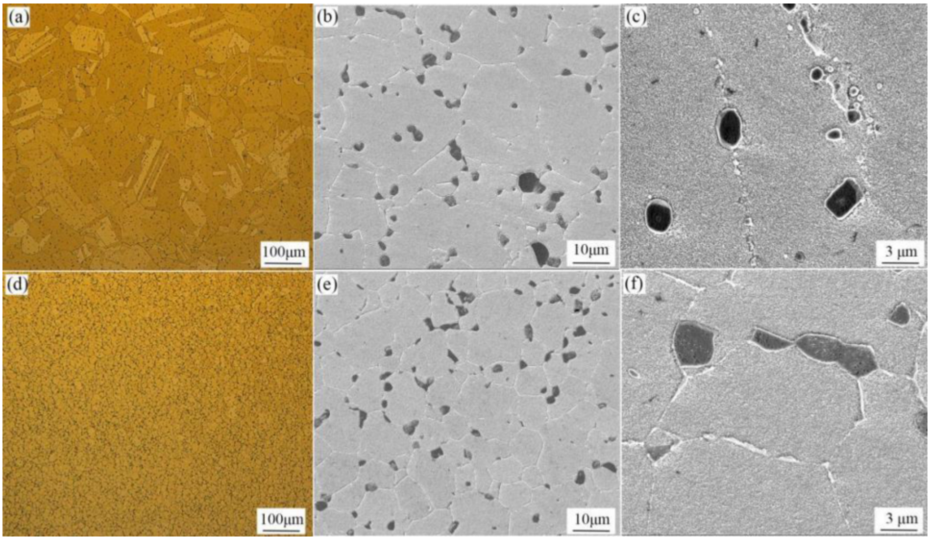

Figure 4. The grain and γ’ phase microstructure of stress rupture specimens. (a)-(c) Coarse-grain specimen; (d)-(f) Fine-grain specimen.

Sampling along the chord direction of the disc was taken to test the high temperature stress rupture behavior of the GH4151, as shown in table 3. The data indicates that the stress rupture lifetime reduced more obviously with decreasing grain size. At the same test condition, it reduced from 82.5 h to 33.5 h as the grain size decreased from 22.3 µm to 11.1 µm, which decreased by 59.4%. Moreover, the elongation rate increased from 6.60 % to 25.48 % as the grain size decreased from 22.3 µm to 11.1 µm, which increased by 286%.

Table 3. Stress rupture properties of coarse-grained and fine-grained specimen.

	Temperature /Stress	Time/h:m in	Average time/h	Elongation δ/%	Average δ/%
Coarse-grain specimen	800°C /500MPa	93:25	82.5	5.92	6.60
		71:35		7.28	
Fine-grain specimen		32:20	33.5	20.24	25.48
		34:40		30.72	

The influence of grain size on the stress rupture behavior of GH4151 at 800 °C/500MPa was studied further. Figure 5 exhibits the rupture fracture morphology at 800 °C/500MPa. It can be seen from the figures 5(a)-(c) that the surface is mixed fracture morphology, the surface shows quasi-cleavage morphology, which is brittle characteristics, and cracks occur on the grain boundaries of large grains and propagate along the grain boundaries; while small grains show good plasticity. It can be seen from figures 5(d)-(f) that there are local dimples in fracture morphology, showing plastic characteristics for fine-grain specimen, and less cracks occur at the grain boundaries. From the microstructure distribution on the fracture side, as shown in figure 6, it can be seen that the distribution characteristics of the phase under the two conditions are consistent. There are more obvious grain elongation phenomenons for fine-grain specimen.

The start of dislocations in crystals is closely related to temperature. At high temperature, thermal activation promotes the movement of dislocations, and more slip systems are opened. At this time, the grain boundary, as a region with higher energy, will also produce relative movement between grains under the action of stress, which will make the grain boundary lose its obstruction to deformation. With the increase of grain size, the grain boundary area and fracture propagation channels decrease, thus prolonging the fracture life of samples. Coarse grains have poor coordinated deformation ability among grains. Therefore, the plasticity is lower than that of fine grain samples.

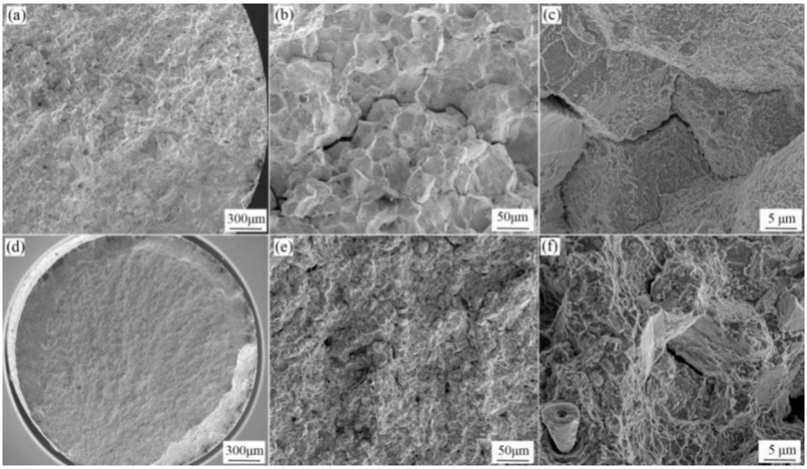

Figure 5. Fracture morphology of rupture properties specimens. (a)-(c) Coarse-grain specimen; (d)-(f) Fine-grain specimen.

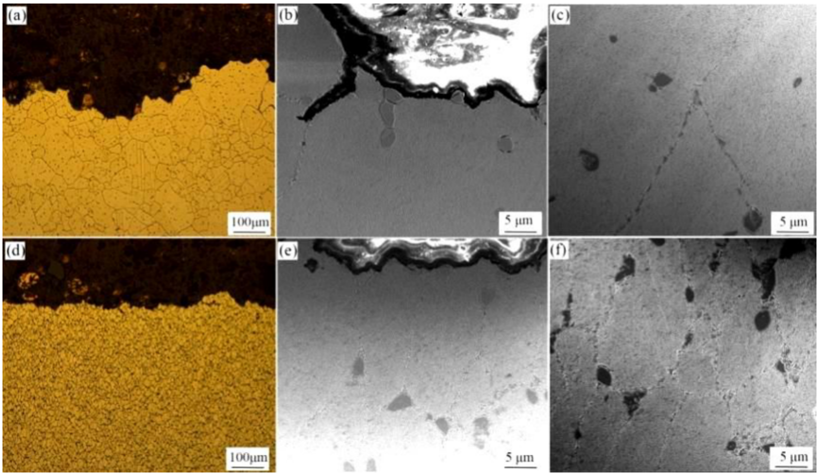

Figure 6. Microstructure characteristics of fracture side. (a)-(c) Coarse-grain specimen; (d)-(f) Fine-grain specimen.

The dislocation morphology of stress rupture specimens is shown in figure 7. As shown in figure 7, the coarse-grained microstructure has larger grain size, longer and more slip bands and higher local stress concentration, which is consistent with the literature report [23]. Therefore, more uneven intragranular deformation will occur in coarse grain microstructure. This will lead to a decrease in grain boundary sliding due to less grain boundary for coarse-grain specimen. Therefore, dislocations will travel a longer distance before reaching the grain boundary, which will produce more dislocation accumulation within grain and delay the activation process of grain boundary sliding. Therefore, the contribution of grain boundaries in the whole deformation process will decrease due to the increase of grain size, which makes stress rupture life of coarse-grain specimen increase. In addition, during deformation, grain boundary sliding and grain rotation are difficult for coarse-grain specimen, and the deformation of surrounding grains is not easy to coordinate, and the stress concentration is relatively high. Finally, the non-uniform deformation in coarse crystals leads to the decrease of plasticity.

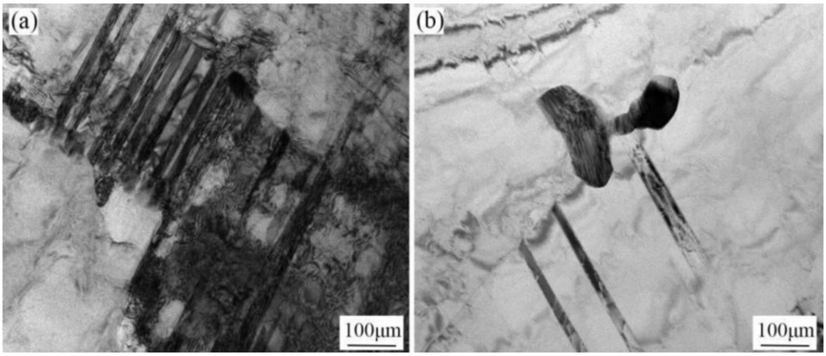

Figure 7. Dislocation configuration near fracture of coarse grain (a) and fine grain (b).

4. Conclusions

The influence of grain size on tensile and stress rupture behavior of GH4151 was investigated. The results are as follows:

(1) The tensile strength at room temperature of fine-grained samples are higher, and the plasticity is also higher.

(2) The atoms on the grain boundary are often irregularly arranged and there are impurities and defects, and fine grains can increase the grain boundary, which can effectively prevent dislocations from passing through and improve the strength of GH4151 alloy.

(3) At the same test condition, it reduced from 82.5 h to 33.5 h as the grain size decreased from 22.3 μm to 11.1 μm, which decreased by 59.4%. Moreover, the elongation rate increased from 6.60 % to 25.48 % as the grain size decreased, which increased by 286%.

(4) The coarse-grained specimen has larger grain, longer and more slip bands and higher local stress concentration within grain, which lead to dislocations to travel a longer distance before reaching the grain boundary, which makes stress rupture life of coarse-grain specimen increase. In addition, during deformation, grain boundary

sliding and grain rotation are difficult for coarse-grain specimen, and thus it is not easy for surrounding grains to coordinate deformation. At this time, the stress concentration is relatively high due non-uniform deformation for coarse-grain specimen, which makes cracks easy to initiate and plasticity decrease.

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