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Evaluation of Mechanical Properties of a Superalloy Disk with a Dual Microstructure

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Abstract. The main purpose of this paper is to evaluate the mechanical properties of a FGH96 alloy disk with a dual microstructure. FGH96 is a powder metallurgy (P/M) processed disk alloy, which was developed in the 1990s in China. The manufacturing processes used to produce the FGH96 disk with a dual grain structure consisted of atomization by plasma rotating electrode process (PREP), hot isostatic pressing (HIP), isothermal forge, special heat treatment for obtaining dual grain structure and final heat treatment. The disk was cut up and completely evaluated. Mechanical properties, including tensile, stress rupture, plastic creep, low cycle fatigue, fatigue crack growth rate, fracture toughness, impact and hardness, were tested at room and higher temperatures. In addition, a detailed grain characterization of the disk, from rim to bore, was also presented.

Introduction

In recent years a new technology has been developed to manufacture turbine disks with dual microstructure. This kind of disks can meet the design requirements for that a much higher tensile strength and a low cycle fatigue (LCF) life for large centrifugal stress in the bore region, while superior high temperature creep and fatigue crack-growth properties are necessary in the rim region to withstand high temperatures as well as high thermal and centrifugal stress. Some methods for producing dual-microstructure components have been described in literatures [1, 2, 3, 4]. All of them have the same principle. The disk is first prepared usually by isothermal forging to have a uniform fine grain microstructure. Then during a special heat treatment a temperature gradient is established from rim to bore of the disk. The rim region is held above the γ' solvus temperature to remove γ' precipitates, that allows grain growth to provide a coarse grain microstructure. While the bore region remains below the γ' solvus temperature, the grain growth is restricted by γ' precipitates, and that retains the initial fine grain microstructure.

FGH96 is a powder metallurgy (P/M) processed nickel-base superalloy, which was developed in the 1990s in China and has been used for manufacturing the rotor components of aircraft engines. This alloy has a nominal composition in mass percent of 2.2Al-0.01B-0.025C-0.01Ce-13Co-16Cr-4Mo-0.8Nb-3.7Ti-4W-0.038Zr-Bal. Ni [5]. The mass fraction of γ' in heat treated FGH96 alloy is about 34.6% [6]. In a previous paper the effects of grain size on mechanical properties of FGH96 alloy were studied [7]. It was found that specimens with fine grain size offer better tensile and fatigue properties while specimens with coarse grain size offer better stress-rupture and creep properties. On this base, a FGH96 disk was produced and treated to have a dual microstructure. This paper presented the characterization of the microstructure and mechanical properties in bore, web and rim regions of the disk.

Materials and Procedure

FGH96 disks were produced by a processing rout with hot isostatic pressing plus isothermal forge. In powder manufacture, vacuum induction melted rods were atomized by plasma rotating electrode process (PREP). The powder was canned in vacuum, hot isostatically pressed and then isothermally forged into a disk with dimensions of about 460mm diameter and 80mm thick (Figure 1). The disk was firstly treated by a special process to acquire a dual grain structure. Subsequent final heat treatment included a subsolvus solution at 1100ºC/1.5 hours followed by a 600ºC salt quench and an aging treatment (860ºC/8 hours, air cool). The disk was machined and then cut into sections for microstructural features evaluating and mechanical properties testing.

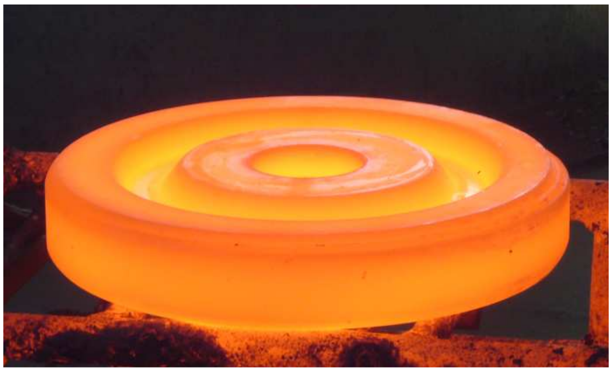


Figure 1. The experimental disk during heat treatment.

Microstructural Characterization

Grain sizes were determined on a transverse macro-section. Figure 2 shows the locations chosen for grain size assessment and the measuring results (in ASTM). Converting the measuring data to a matrix, a distribution contour plot of the average grain sizes in the transverse section of the disk can be created (Figure 3). The average grain size varies with radial distance in the disk. In the bore region grain size is about 9.5-11μm (ASTM 10.5-10). The grain size increases to about 45-55μm (ASTM 6-5.5) in the rim region. The transition zone is in web region and about 40mm in width, grain size varies from 16μm to 45μm (ASTM 9-6). Typical grain microstructures representative of different regions are shown in Figure 4. As shown in Figure 5, γ' precipitates in different regions of the disk have also different distributions. A bimodal distribution of γ' precipitates in bore region can be observed. But in web and rim regions, γ' precipitates appear to be a tri-model distribution.

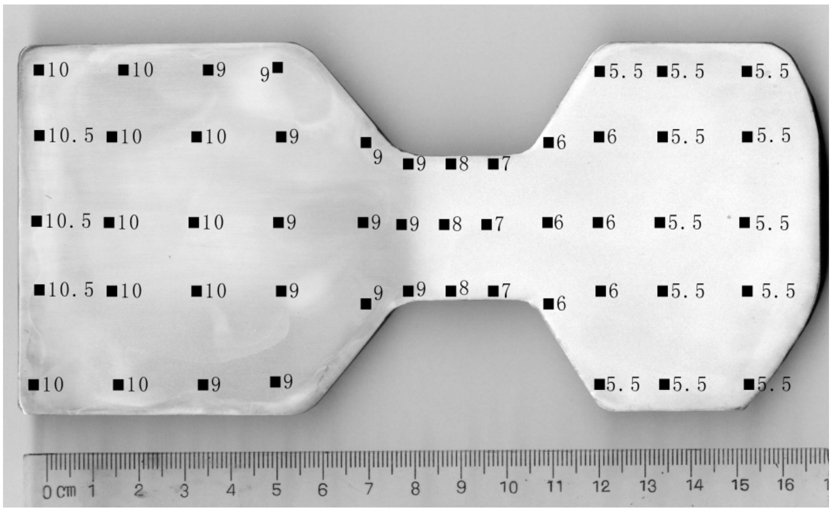


Figure 2. Measuring locations and results of the grain size (in ASTM) assessment on a transverse macro-section of the disk.

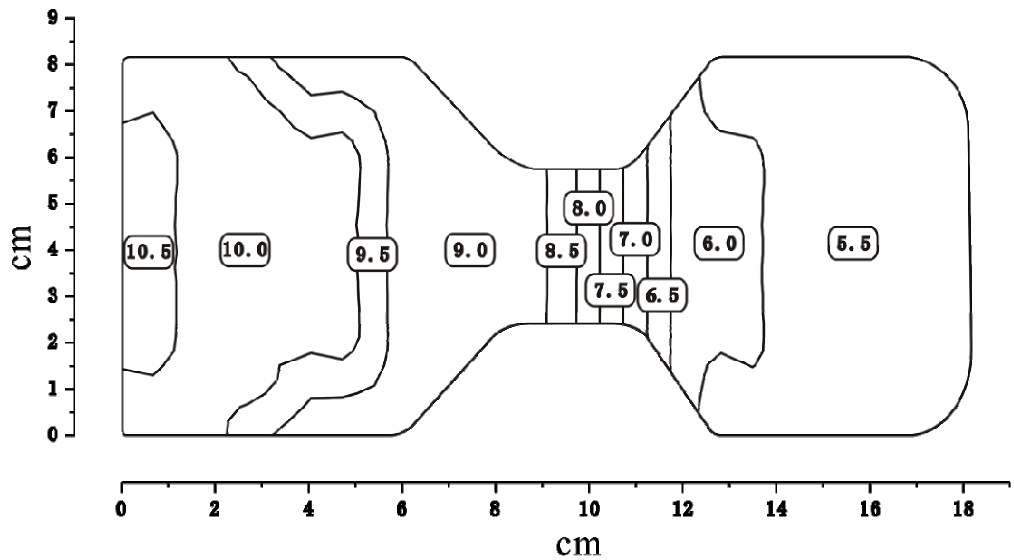
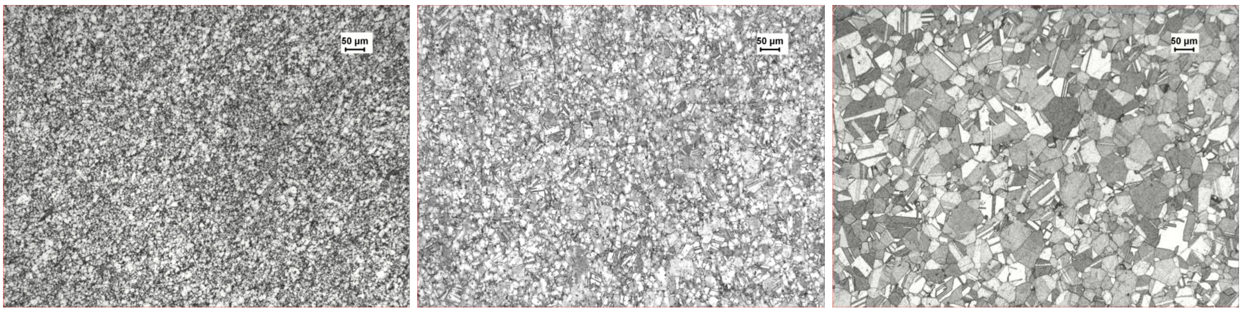
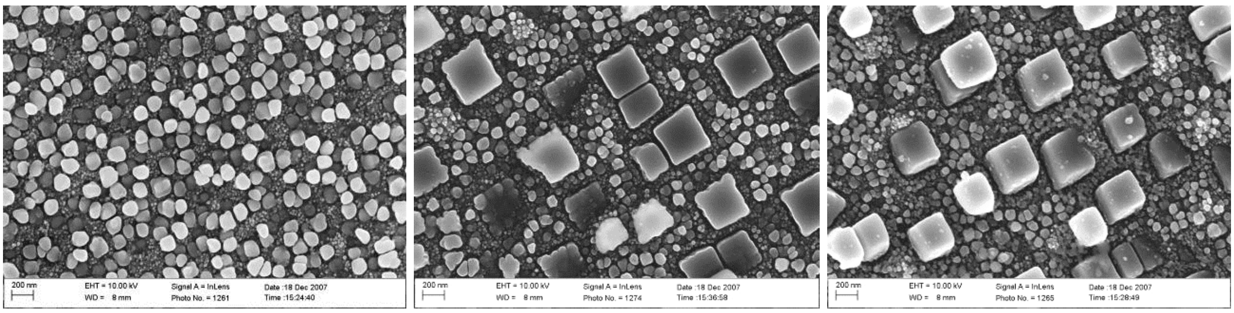


Figure 3. Average grain size (in ASTM) distribution of the disk



Bore Web Rim

Figure 4. Typical grain microstructures in bore, web and rim regions of the disk



Bore Web Rim

Figure 5. Morphologies and distributions ofγ' precipitates in bore, web and rim regions of the disk

Mechanical Properties

Mechanical properties, including tensile, stress rupture, plastic creep, low cycle fatigue, fatigue crack growth rate, fracture toughness, impact and hardness were tested on specimens from different regions of the disk. Tensile tests were conducted at room temperature, 650ºC and 750ºC on specimens from each different microstructural region. The results were shown in Table 1. The disk exhibit excellent strength at room and high temperature. The test data reveal obviously a variety correlated with corresponding grain size. Stress rupture properties were determined at 550ºC/1150MPa, 650ºC/1000MPa, 750ºC/650/690MPa for bore region and 650ºC/1000MPa, 750ºC/650/690MPa for rim region. The results were shown in Table 2. At 550ºC, the fine grain bore region of the disk has outstanding rupture life on high stress level. But at 650ºC and 750ºC, the coarse grain rim region offers better stress rupture properties than the fine grain bore region. Creep specimens were examined at 550ºC/1100MPa/100hours for bore region and 750ºC/450MPa/100hours for rim region. The results were shown in Table 3. Both bore and rim regions of the disk display a good creep property. Low cycle fatigue tests were performed at 400° C, 538° C on bore specimens and 650° C, 750° C on rim specimens using a triangular waveform to a total strain range of 0.85 percent and a strain ratio of $R_\varepsilon = \varepsilon_{min}/\varepsilon_{max} = 0$, using a frequency of 0.33 Hz. The LCF properties, both in bore and rim, are satisfactory as shown in Table 4. Fatigue crack growth tests were done at 650° C using a maximum load of 4.165kN and load ratio of 0. All specimens from bore, web and rim regions had a rectangular gage section 25mm wide and 10mm thick, with a surface flaw about 0.1mm wide and 15mm deep produced by electro-discharge machining. Tests were performed with 5s and 90s dwells at maximum load. The results were illustrated in Figure 6. The resistance to dwell crack growth of the disk increases radially from bore to rim. Fracture toughness tests were conducted at room temperature. Test conditions and results were exhibited in Table 5. The value of provisional fracture toughness K_Q in rim region is higher than that in bore region. Impact and hardness were measured at room temperature. The results were shown in Table 6. The values of impact of the disk increase from bore, web to rim. The values of hardness vary inversely.

Table 1. Results of tensile tests

Location	Temp. (° C)	U.T.S. (MPa)	0.2% Y.S. (MPa)	Elongation (%)	R.A. (%)
Bore	22	1590	1210	18.0	21.0
Bore	22	1610	1210	22.5	30.5
Web	26	1490	1050	22.5	27.0
Web	26	1570	1150	21.5	29.0
Rim	26	1480	1040	23.0	28.5
Rim	26	1480	1030	20.0	23.0
Bore	650	1500	1110	13	16.5
Bore	650	1460	1090	17	21.0
Web	650	1440	1050	16.0	17.5
Web	650	1480	1080	17.0	18.0
Rim	650	1420	985	15.0	19.0
Rim	650	1420	975	21.0	21.5
Bore	750	1160	1040	13	16.0
Bore	750	1190	1050	12	16.0
Web	750	1140	1010	13.0	15.5
Web	750	1170	940	15.0	17.0
Rim	750	1140	915	11.0	14.5
Rim	750	1170	930	13.0	15.5

Table 2. Results of stress rupture tests

Location	Temp. (° C)	Stress (MPa)	Rupture life (hours)	Elongation (%)
Bore	550	1150	418:25	5
Bore	650	1000	42:41	8
Rim	650	1000	71:47	3
Bore	750	690	12:25	13
Rim	750	690	32:53	12
Bore	750	650	18:12	14
Rim	750	650	69:55	14

Table 3. Results of creep tests

Location	Temp. (° C)	Stress (MPa)	Time (hours)	Creep Elongation%
Bore	550	1100	100	0.088
Rim	750	450	100	0.062

Table 4. Results of low cycle fatigue tests

Location	Temp. (^{o}C)	Fatigue life (cycles)
Bore	400	15463
Bore	538	15265
Rim	650	6750
Rim	750	4949

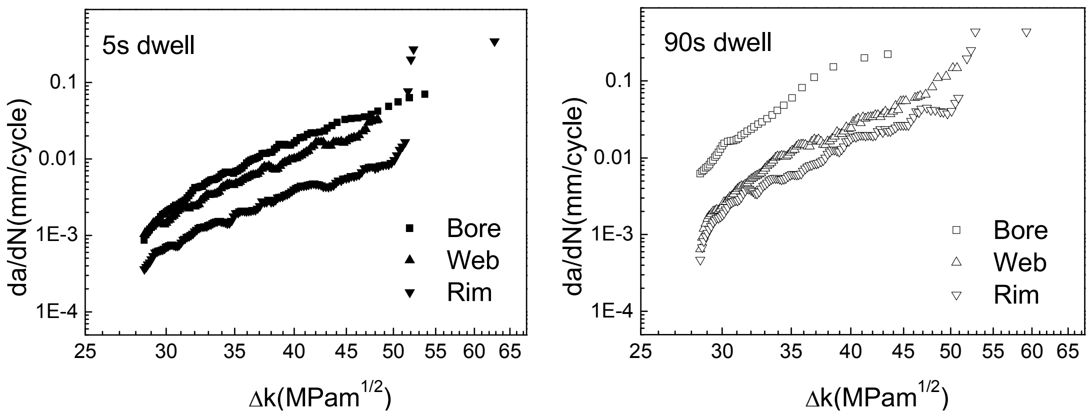


Figure 6. Dwell crack growth rates of the disk

Table 5. Conditions and results of fracture toughness tests

Location	Specimen thickness B (mm)	Specimen width W (mm)	Crack length a (mm)	Condition Load P_q (kN)	Maximum load P_{max} (kN)	K_Q ($MPam^{1/2}$)	Valid
Bore	25.08	50.02	26.71	83.125	108.438	158	No
Rim	25.14	50.17	26.97	89.375	104.688	172	No

Table 6. Results of impact and hardness tests

Location	Impact, A_{KU2} (J)	Hardness (HB)
Bore	37	440
Web	50	411
Rim	51	409

Summary

A FGH96 superalloy disk with a dual microstructure was sectioned for microstructural features evaluating and mechanical properties testing. The disk has a fine grain structure (ASTM 10-10.5) in the bore region and a coarse grain structure (ASTM 5.5-6) in the rim region. The grain size transition zone locates in the web region of the disk and is about 40mm in width. The γ' precipitates in the disk appear to be a bimodal distribution for the bore region and a tri-model distribution for the web and rim regions. Mechanical testing displayed the fine grain bore region has a high tensile and rupture strength, exceptional LCF life and creep resistance at lower temperature. At higher temperature, the coarse grain rim region displays better properties in stress rupture, creep, fatigue crack growth, fracture toughness and impact than that of bore region. The properties of the grain transition web region are intervenient between bore and rim regions.

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