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The Microstructure and Mechanical Properties of Inconel 718 Fine Grain Ring Forging

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Abstract

The microstructure and mechanical properties of fine-grained Inconel 718 ring forging were investigated in this paper. The results indicated that the fine-grained ring forgings can be obtained by forging the fine-grained Inconel 718 bars. The grain size can be as fine as ASTM 10 and the precipitated δ phase are spherical. Heat treated at 980°C/1h/water cooling + 620°C /12h/air cooling, the ring forgings possessed very good mechanical properties. The impact toughness can be over 100J. In the fatigue test with the stress ratio -1, when the theoretical stress concentration factor is 1 and 2.7, the maximum stress for 10^7 fatigue cycles is over 620 MPa and 260 MPa, respectively.

Introduction

Inconel 718 alloy has been used world-wide in aerospace, aircraft, oil, and chemical industries, and also nuclear power plants because of its high strength, excellent ductility, good formability and weldability etc [1-3]. To meet the demands of different service conditions, the die forging process has been investigated intensively in the past few years. Besides two conventional forging processes, including forging driven by hydraulic presses or hammers, and some advanced forging processes, such as hot die forging, insulation die forging and isothermal forging, have been developed to manufacture fine grains forgings. The products of these processes have been applied significantly in new power units [4-6].

Inconel 718 alloy fine grain ring forgings which were used to manufacture a key part of one new power unit. The part should have excellent impact toughness and high cycle fatigue properties to meet the complicated cyclic loading seen in service. The microstructure and mechanical properties of fine grain ring forgings have been investigated in this paper. Impact toughness and high cycle fatigue properties under different stress concentrations were also studied based on the analysis of conventional mechanical properties.

Material and experimental procedures

Trial material was obtained from the Inconel alloy 718 bar by using radial forging machine, the bar was manufactured in Special steel business Unit of Baosteel. The main chemical composition of Inconel 718 trial material is shown in table 1. The melting process of the alloy was VIM+ESR (Ar protected). After homogenization the ESR ingot was forged into octagon bar (220mm) by hydraulic press, then the octagon bar was forged into round bar (Φ105mm) by 1300t radial forging machine. The average grain size of the bar is ASTM 7 and 9.

Table 1 Chemical composition of Inconel 718 alloy (wt%)

C	Si	Mn	S	P	Cr	Ni	Mo	Nb	Ti	Al	Fe
0.024	0.06	0.02	0.002	0.003	18.84	53.64	3.08	5.23	0.95	0.53	17.62

Ring forgings were obtained from the bar stock, which has undergone a process of forge-reheat-forge by using 3000t oil hydraulic press. At the first pass of forging process, the bar stock was heated to 990~1020°C, then forged into pancake and cooled by water immediately. At the second pass of forging, the pancake was heated to 990-1020°C again, and the heat preservation of the billets were by use of applied insulation. The mold was heating to 600-650°C, and the billets were forged into the final shape. The dimensional sketch of ring forging is shown in Figure 1. The heat treatment process was two step treatments consisting of solution treatment at 980°C for 1 hour and water quenched, then reheated to age at 620°C for 12 hours, and then air cooled.
Tensile test was conducted on MTS-810 machine; the Charpy-type U notched specimen was used in impact test which carried out on a JB-30 impact machine. Rotary bending fatigue test was conducted on an E4 fatigue machine with a 80-85Hz test frequency and stress ration of -1. Two kinds of samples were chosen for the fatigue test, a smooth specimen and notched specimen with 0.5mm notch radius, the theoretical stress concentration factor is 1 and 2.7, respectively.

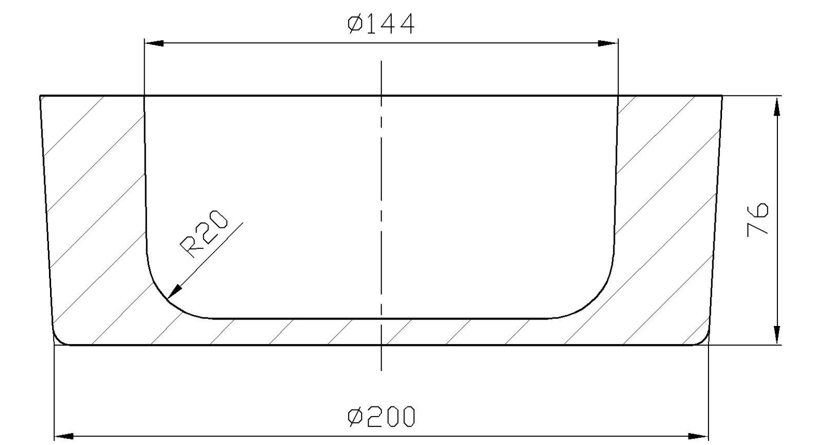
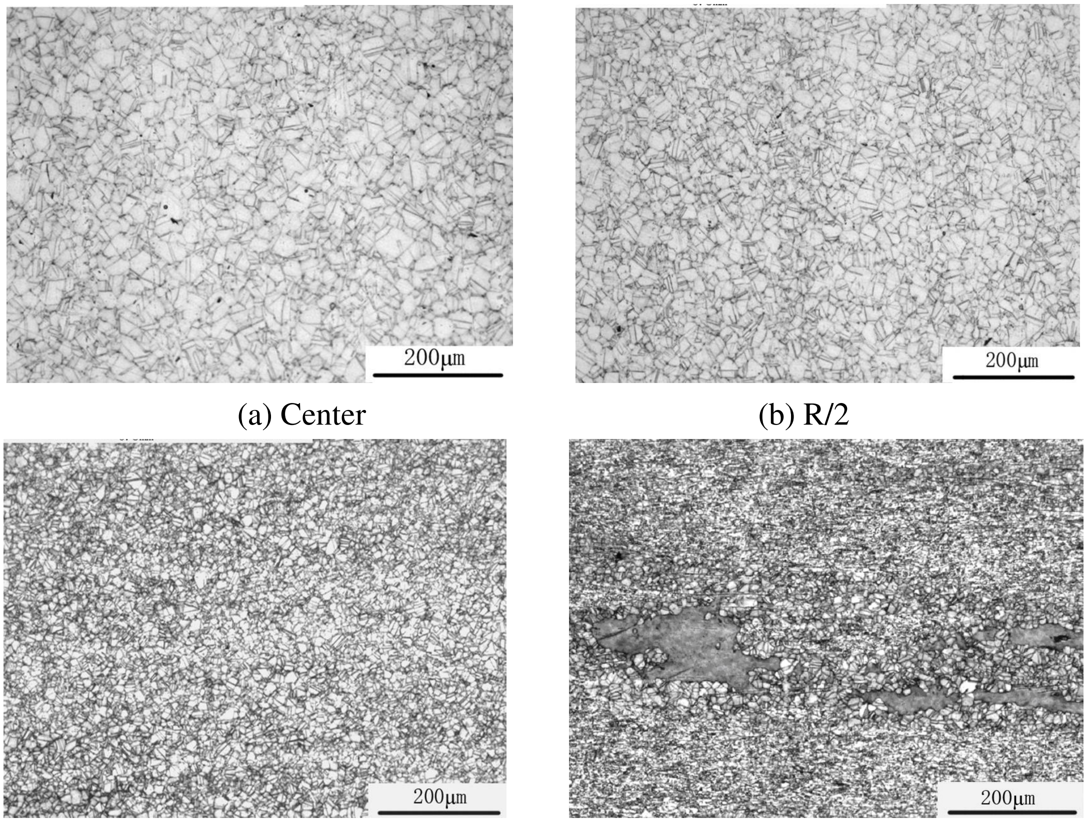


Fig1. A dimensional sketch of ring forging

Results and discussion

Microstructure of Billet and the Ring Forging

The microstructure of Φ105mm radial forging bar is shown in Figure 2. Typical grain size at center and mid-radius locations of the bar are between ASTM 7 and 9, while the average grain size at bar surface is about ASTM 10, there were also some ASTM 2-4 coarse grains surrounded by ASTM 10 fine grains. In general, fine grain Φ105mm radial forging bar is beneficial in producing fine grain forgings.

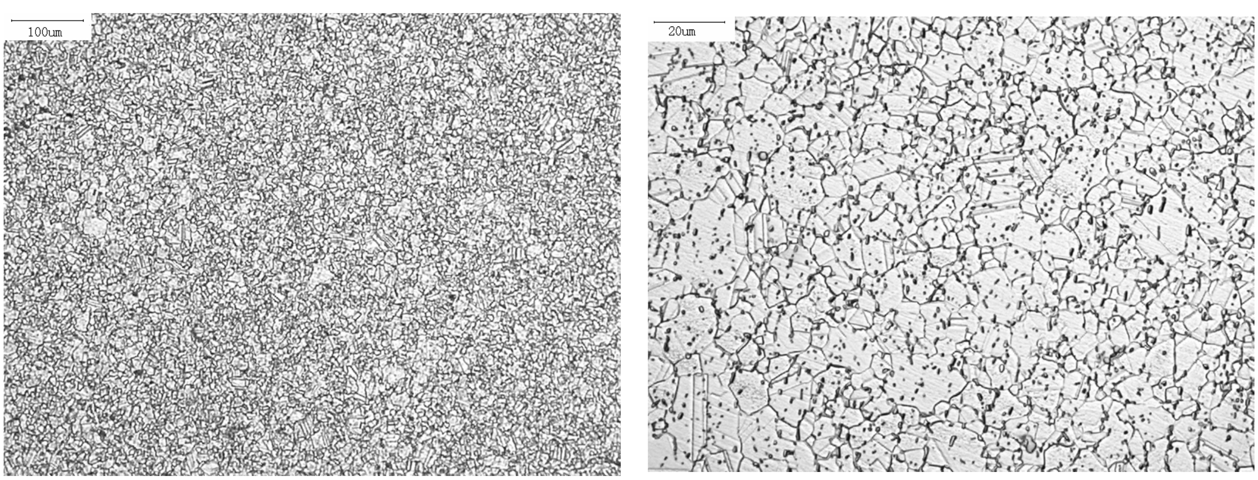


(a) Center (b) R/2

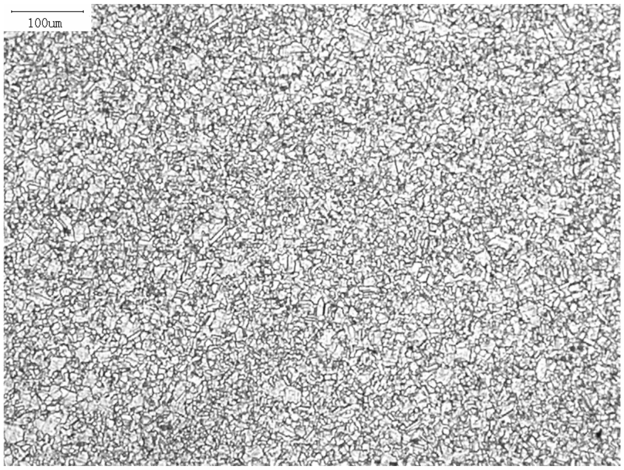
(c) Near surface position (d) Coarse grains near surface position

Fig.2. Grain structure of Φ105mm bars

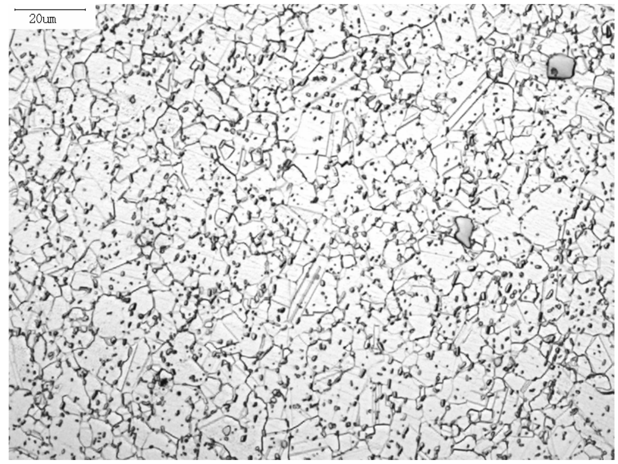
Fig.3. shows the microstructure with δ phase distribution at different positions of ring forging. It can be seen that δ phase could be fully spheroidized after the bars were die forged at the critical solution temperature of δ phase. The average grain size at different positions of ring forgings are estimated to be finer than ASTM 10, Mid-radius to the surface grain size are determined to be uniform and fine. This kind of microstructure is of great benefit for forging parts to have excellent ductility and high fatigue strength.



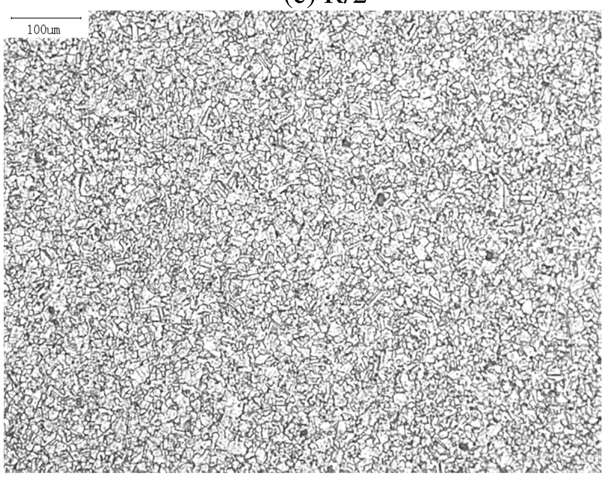
(a) Near inner surface position (b) Near inner surface position



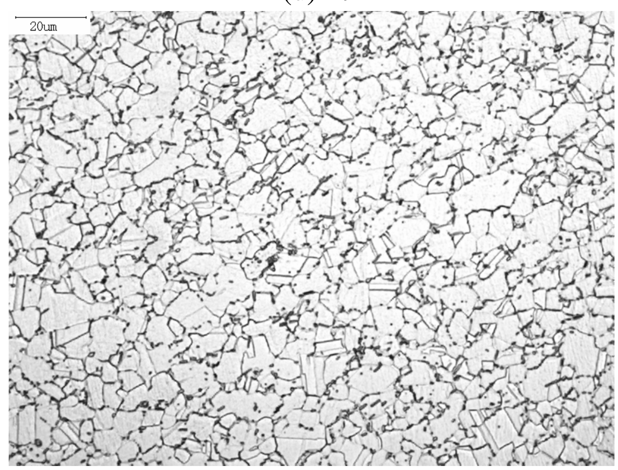
(c) R/2



(d) R/2



(e) Near outer surface position



(f) Near outer surface position

Fig3. The δ phase and grain microstructure of the ring forging

The SEM micrograph of δ phase distribution is shown in fig.4. Fine δ phase particles have been observed, and they appear to be spherical in shape.

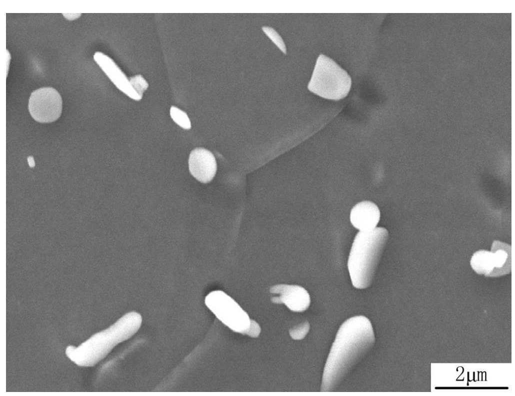


Fig.4. The SEM image of δ phase microstructure of ring forging

Results presented in literature [7] show that Inconel 718 benefits from hot die forging using die temperature at 900-930°C and billet temperature 990-1020°C for billet when the hot die forging technique is used to forge Inconel 718. If the billet grain size is finer than ASTM 7, then hot die forging under a large deformation ratio can achieve a grain size finer than ASTM 10. In our investigation experiment, heat insulating hot die forging technique is applied, requiring die temperature at 600-650°C. Fine grain forging with the grain size finer than ASTM 10 can be obtained by this route, which greatly reduces the requirement for high temperature capable of die material. This technique can reduce the production costs considerably.

Mechanical Properties of the Ring Forging

After using the heat treatment designed for this investigation, the forging mechanical properties, presented in table 2, and 846-0010 heat number is the typical Inconel 718 forging data. Yield strength is greater than 900MPa and impact toughness can be over 100J.

Table 2 Mechanical properties of tested ring forging

Heat number	UTS	YS	A	Z	Impact
	MPa	MPa	%	%	J
630-0909 Ring Forging	1240	905	34	48	100
	1240	920	36	48	102
630-0912 Ring Forging	1260	910	31	41	119
	1250	900	32	46	120
846-0010 Typical Forging	1360	1170	23	45	48
	1360	1180	22	44	50

Results presented in literature [2] show that the peak precipitation temperature of δ phase for inconel718 alloy is about 930°C.The δ phase begins to dissolve at 980°C, completely dissolved at 1020°C; γ" phase begins to precipitate at 650°C, and begins to dissolve from 840 to 870°C, it can be dissolved completely at 950°C; γ’ phase precipitates at 600°C, and begins to dissolve at 840°C. The precipitation of δ phase can be greatly restrained at water cooling after solution treatment, and the content of δ phase is lower than for standard heat treatment (720°C /8h, furnace cooling to 620°C by 50°C/h, and then 8h air cooling). The chemical composition of δ phase tested by APD-10 type X-ray diffractometer at different heat treatment presented in table 3.

Table 3 Chemical composition of δ phase by different heat treatment

Item	Element in δ phase (wt%)								Total (wt%)
	Ni	Fe	Cr	Al	Mo	Nb	Ti	Zr	
This heat treatment	1.1481	0.0401	0.0255	0.0016	0.0229	0.4879	0.0481	0.0023	1.7765
Standard heat treatment	1.3387	0.0514	0.0276	0.0018	0.0263	0.5697	0.0573	0.0034	2.0762

When the ring forging was aged at 620°C, the precipitation temperature of γ" phase is suppressed and the alloy was primarily strengthened by γ’ phase, the chemical composition of γ’ phase and γ" phase tested by APD-10 type X-ray diffractometer at different heat treatment presented in table 4. Therefore its strength is lower than that of standard heat treatment Inconel 718. However, with the reduction of strengthen, the ductility and impact toughness is improved.

Table 4 Chemical composition of γ’ and γ" phase by different heat treatment

Item	Element in γ’ & γ" phases (wt%)								Total (wt%)
	Ni	Fe	Cr	Al	Mo	Nb	Ti	Zr	
This heat treatment (γ’ phase only)	2.4106	0.0353	0.1306	0.0668	0.0447	0.6268	0.1588	0.0051	3.4787
Standard heat treatment (γ’ phase + γ" phase)	8.4468	0.2813	0.4750	0.2046	0.1963	2.3420	0.5530	0.0197	12.5187

<u>High Cycle Fatigue of Ring Forgings</u>

The S-N curve of as heat treated Inconel718 ring forgings (smooth and notched specimen) at room temperature are shown in Fig 5 and Fig 6, respectively. It can be seen from the graphs that rotating bending high cycle fatigue strengths of the ring forgings are 620MPa and 260MPa at with the stress concentration factor Kt= 1 and 2.7, respectively. The forgings exhibit a good resistance to high cycle fatigue.

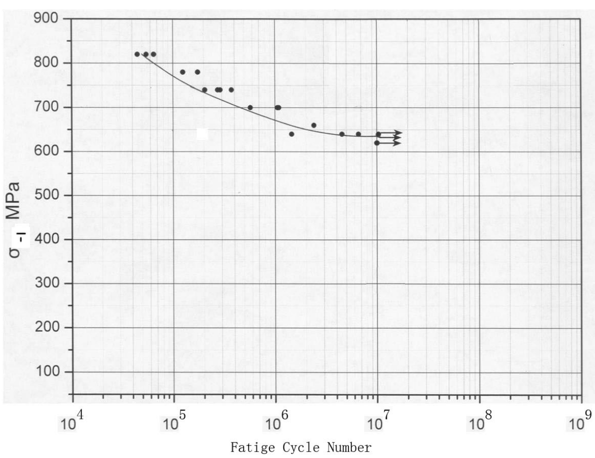


Fig5. The S-N curve of ring forging (Kt=1)

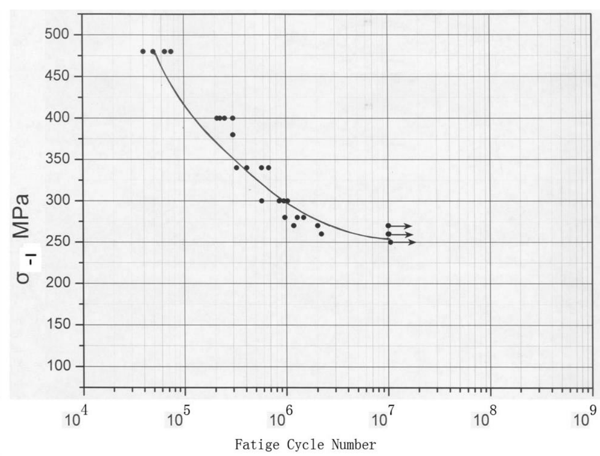


Fig6. The S-N curve of ring forging (Kt=2.7)

It is clear that fine grain structure produces a greater grain boundary area, which can reduce fatigue crack propagation. Therefore, the high cycle fatigue property will be improved if the grain size can be refined [9-10]. Some researches have commented on the influence of grain size on the fatigue properties, and a relation expression like Hall-Petch type formula was summarized from the past study:

$$\sigma_{1} = \sigma_0 + K_g d^{1/2}$$

Where, σ_{-1} is fatigue strength, σ_0 and K_g are material constants, d is average of grain size. In our investigation the average grain size of the forgings is finer than about ASTM 10. The typical spherical δ phase was obtained by insulation die forging at the critical dissolution temperature of δ phase. So the embrittlent effect of δ phase is weak because of the optimization from two aspects, quantity and shape of δ phase, which is benefit to improve high cycle fatigue properties.

Conclusions

(1) The fine-grained ring forgings can be obtained by insulation die forging from the bars, the grain size can be ASTM 10 or finer. Most of the δ phase is spherical and granular, and the rest is short rod-like δ phase.

(2) A good balance between strength and ductility can be achieved after special designed heat treatment of ring forgings with a fine-grained structure which resulted in the impact toughness can be over 100J.

(3) The excellence of high cycle fatigue property is demonstrated for these fine grain ring forgings. The rotating bending high cycle fatigue cycles limit $\sigma_{-1}^{10^7}$ is 620 MPa and 260 MPa, at stress concentration factor of 1 and 2.7, respectively.

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