CURRENT PRODUCTION STATUS OF ALLOY 718 TURBINE DISKS IN CHINA

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Abstract

For the past few years the production of high quality alloy 718 turbine disks has made great strides in China. A closer working arrangement with research laboratories in universities and steel plants has resulted in higher quality components which are comparable to those produced in other countries. The main technology studies which led to the production of quality alloy 718 disks were: (a) effects of Mg on segregation, (b) influence of inclusion control on mechanical properties, and (c) effect of grain size. The mechanical and structural results from a current production turbine disk are presented in this paper.

Introduction

Early in the assessment of turbine disk technology, it was recognized and agreed on that a cooperative effect between university research and factory manufacturing technologies was necessary to produce high quality turbine disk components. The three technical areas that seemed to be the most important for successful production of turbine disks were:

1. Better understanding of the role that Mg plays in countering the effects of detrimental trace elements in raw materials but also, Mg's influence on the mechanical properties.
2. The influence of inclusions and stringers which form large amounts of MC and TiN particles.
3. The role of grain size and phases on the mechanical properties.

This paper describes some of the research results in these three areas which have been successfully transferred to industry and incorporated into production of alloy 718 turbine disks.

Materials and Experimental Procedure

Eleven experimental heats of alloy 718 with varying of magnesium (Group A, Heat 1, 2, 3, 4 and Group B, Heat 42, 44), carbon (Group C, Heat 5, 6 7) separately and addition of magnesium and carbon simultaneously (Group D, Heat 8, 9) were melted in 50 Kg VIM furnace. Two production heats (Group E and F) were VIM + VAR melted for 406 mm diameter ingots. Chemical composition and alloy designation are listed in Table I.

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Table I. Chemical Composition of Investigated Alloy 718 (wt.%).

Group	Heat	C	Mn	Si	S	P	Cr	Ni	Mo	Al	Ti	Nb	Mg
A	1	0.060	0.10	0.13	0.002	0.003	19.59	52.09	3.01	0.58	1.00	5.22	0.0002
	2	0.055	0.10	0.17	0.002	0.003	19.72	52.47	2.96	0.56	0.99	5.09	0.0044
	3	0.055	0.10	0.13	0.002	0.003	19.65	52.18	2.98	0.60	1.00	5.12	0.0090
	4	0.060	0.10	0.12	0.002	0.003	19.75	52.27	3.00	0.61	1.02	5.12	0.0180
B	42	0.030	0.10	0.03	0.006	0.009	19.14	52.00	3.12	0.43	1.04	5.00	
	44	0.025	0.10	0.07	0.005	0.009	18.98	52.90	3.15	0.45	1.02	5.10	0.0094
C	5	0.015	0.005	0.10	0.002	0.006	18.92	52.98	3.01	0.52	0.98	5.30	0.0005
	6	0.045	0.005	0.09	0.001	0.007	18.89	52.14	3.02	0.53	0.98	5.31	0.0005
	7	0.065	0.007	0.09	0.002	0.006	18.80	52.12	2.99	0.54	0.98	5.40	0.0005
D	8	0.007	0.008	0.08	0.003	0.006	18.99	52.12	3.05	0.54	1.00	5.40	0.0070
	9	0.040	0.007	0.08	0.003	0.006	18.82	52.18	3.07	0.57	1.00	5.37	0.0066
E	3610	0.025	0.004	0.09	0.005	0.004	18.57	52.63	3.04	0.50	0.99	5.26	0.0047
F	7H21-019**	0.040	0.030	0.11	0.002	0.004	18.50	52.43	2.95	0.47	1.00	5.17	0.0050

* Fe-balance , B-0.002-0.006%

**O-3 ppm , N-45 ppm , H-0.9 ppm

All ingots were homogenized and eleven of the experimental heats were forged to 40 mm square bars. Heat 1-9 were rolled down to 20 mm round bars for tests. Part of the ingot of production heat 3610 was forged down to 380 × 80 mm pancakes with fine (ASTM 8) and coarse grain (ASTM 4) sizes to study the effect of grain size. Production heat 7H21-019 was made at the Fushun Steel Plant. Billets of 250 mm diameter with ASTM 5-7 grain size were forged from homogenized ingot. Pancakes of 360 mm diameter were forged by 6000 ton hydraulic press. Finally, fine grain die-forging disks with ASTM 8 grain size were finished under 30,000 ton hydraulic press. One of 435 mm diameter die-forging disks of alloy 718 from production heat was cut up and used for material evaluation testing.

Solidification temperature range (interval) and degree of segregation were determined by a standard heating and cooling method. Metallographic observation and electron-probe chemical composition analyses for elements Nb and Ti were recorded.

Alloy 718 samples for mechanical properties testing were given the ASM 5596C heat treatment, i.e., 950°C/1 hr/AC + 720°C/8 hr/FC 50°C/h → 620°C/8 hr/AC. Mechanical property evaluation included smooth and notch bar tensile and stress rupture, creep, cyclic stress rupture tests with different holding times or LCF tests, creep/fatigue interaction tests and crack propagation rate determination.

Mechanical property test samples from the production disk were cut from the rim of disk which had the ASM 5596C heat treatment.

Structural characterization techniques were carried out by means of optical, SEM and TEM microscopy and fractography analyses.

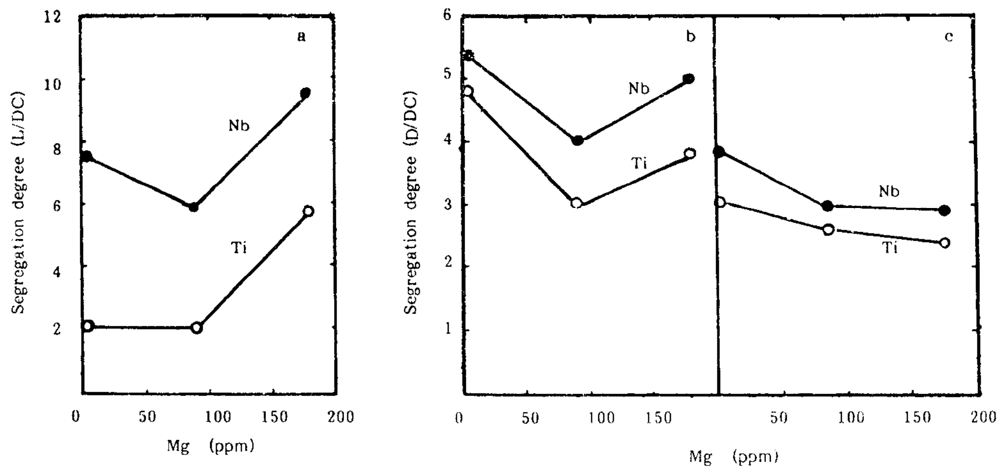


Fig. 1. Mg effect on segregation behavior at solidification (a, b) and after homogenization (c).
L/DC: ratio of retained liquid to the center of dendrite.
D/DC: ratio of interdendrite area to the center of dendrite.

Experimental Results and Discussion

Micro-alloying of Mg

The Mg in alloy 718 has been reported in our previous investigations to concentrate at grain boundaries as equilibrium segregation and changes the grain boundary precipitates δ–Ni_3Nb morphology. Mg additions raise not only high temperature strength in stress rupture and creep/fatigue interaction conditions but also raises the high temperature tensile and stress-rupture ductilities.

Because of the importance of the segregation problems in alloy 718, a better understanding of the Mg effect on solidification and segregation behavior is needed. Table II shows that Mg has no big effect on the temperature interval of liquidus and solidus (ΔT), which normally influence segregation behavior during solidification. A small amount of Mg (less than 100 ppm) does improve the degree of segregation of elements Nb and Ti as shown in Figure 1. The segregation degree is characterized by the element content ratio of final retained liquid to the center of the dendrite (L/DC, see Figure 1a) during solidification and the element content ratio of interdendrite area to the center of dendrite (D/DC, see Figure 1b) after solidification. Higher Mg contents have no beneficial effect on segregation. After homogenization treatment, Mg additions improve the degree of Nb and Ti distribution.

Table II. Mg Effect on Start and Finish Temperatures of Solidification.

Heat	1	2	3
Mg%	0.0002	0.0090	0.0180
Start Temp. (°C)	1348-1343	1342-1339	1343-1339
Finish Temp. (°C)	1100-1090	1100-1090	1100-1090
Solidification Interval (ΔT,°C)	248-253	242-245	243-245

A solidification study, to be presented in another paper, shows that Mg is beneficial in the homogenization of alloy 718 by promoting interdendritic carbide NbC refinement and depressing primary gross Laves phase formation.

The obvious effect on high temperature tensile ductility improvement at 650°C by addition of 50-100 ppm Mg is clearly shown in Figure 2.

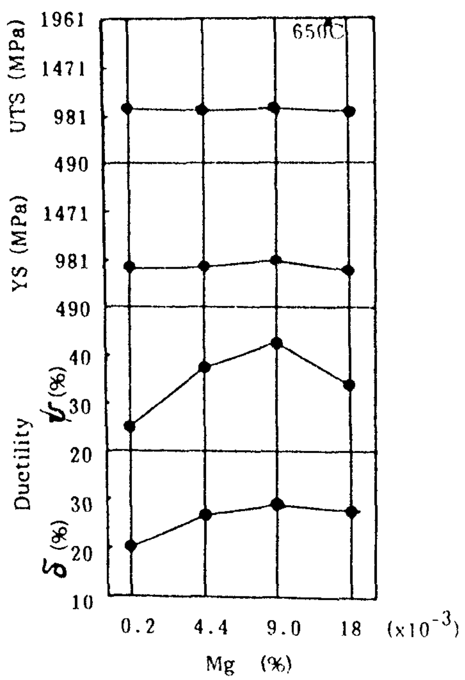


Fig. 2. Mg effect on 650°C tensile properties.

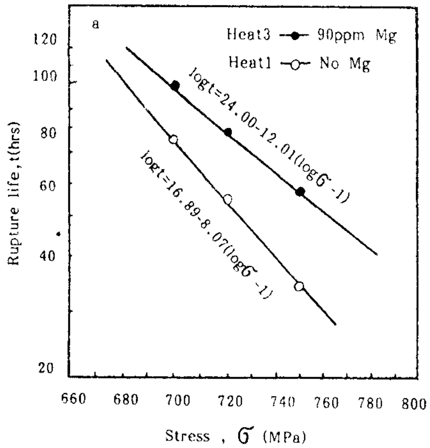
Magnesium addition can prolong stress rupture life, decreases minimum creep rate, increases creep ductility to failure and develops more distinctive secondary and ternary creep stages as shown in Figure 3.

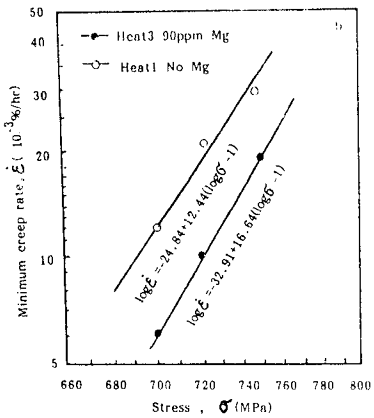
Table III shows Mg addition has almost no effect on activation energy of creep, but does decrease creep stress exponent, n, that is beneficial for the superalloy at service.

Table III. Mg effect on creep activation energy (Q) and stress exponent (n).

Heat	Mg%	Q(Kcal/mol)	n
42	---	133.5	27.11
44	0.0094	137.5	18.34

As concluded in our previous work, one main structural effect of Mg is to change continuous grain boundary δ–Ni_3Nb morphology to discrete globular form which has a retardation effect on intergranular fracture in stress rupture. Grain boundary δ–Ni_3Nb morphology and distribution also influence the creep and fatigue interaction properties and crack propagation rates.





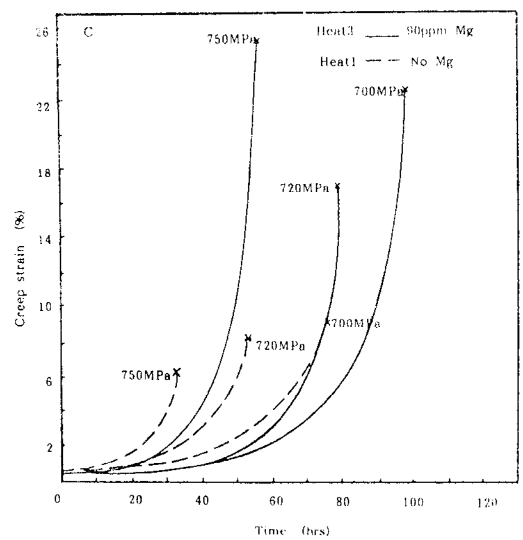


Fig. 3. Mg effect on stress rupture life,
(a) minimum creep rate,
(b) and creep curves
at 650°C.

From the results of our studies on the effects on mechanical properties, alloy 718 with 40-100 ppm Mg was recommended for disk production.

Inclusion Control

NbC or Nb (CN) phases in alloy 718 are to be considered as inclusions which are deleterious for mechanical properties, especially LCF life. Figure 4 shows that the volume fraction of inclusions (V) and the number of inclusions per area (N) are intensively increased with an increase of carbon content; however, carbon does not influence the grain size (D) after the ASM 5596C heat treatment in alloy 718. Detrimental inclusion stringers appear at higher carbon contents (such as > 0.07C) in alloy 718.

Carbon does not influence the tensile strength and ductility in alloys with or without Mg both as shown in Figure 5, but carbon greatly decreases notch stress rupture life especially for alloy 718 without Mg (see Figure 6). In those alloys with higher carbon content, stress rupture notch sensitivity could be impared. Figure 7. shows the carbon effect on decreasing tendency for cycles to failure for LCF tests with different dwelling times (5, 180, 1800 sec) at maximum stress for notch specimens.

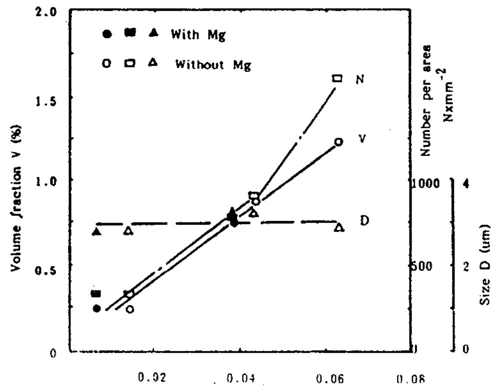


Fig. 4. Carbon effects on volume fraction (V) and number per area (N) of inclusions and the grain size (D).

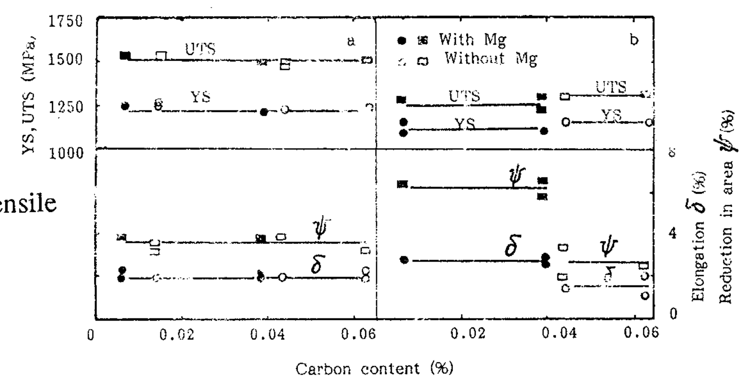


Fig. 5. Carbon effects on tensile properties at 20°C, (a) and 650°C (b).

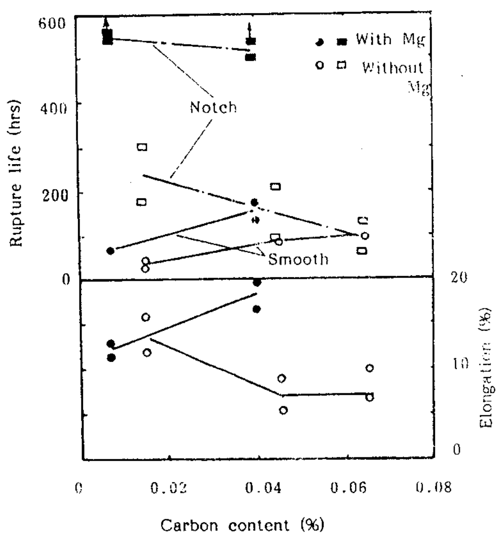


Fig. 6. Carbon effects on smooth and notch bar stress rupture at 650°C, 686 MPa.

The effect of carbon is considered to be deleterious in alloy 718 and hence, a lower carbon content (0.02 - 0.04%) for alloy 718 was recommended to the factories. To promote a cleaner alloy 718 with extra low content of nitrogen, low nitrogen VIM melting technology studies are being conducted in our laboratories prior to application to full scale production in factories.

Grain Size Effect

There is a trend to reduce grain size to achieve high yield strength, good ductility, and long LCF life, but find grain structure has lower creep strength and shorter stress rupture life. The grain size effect on fatigue and creep interaction is very important for disk applications.

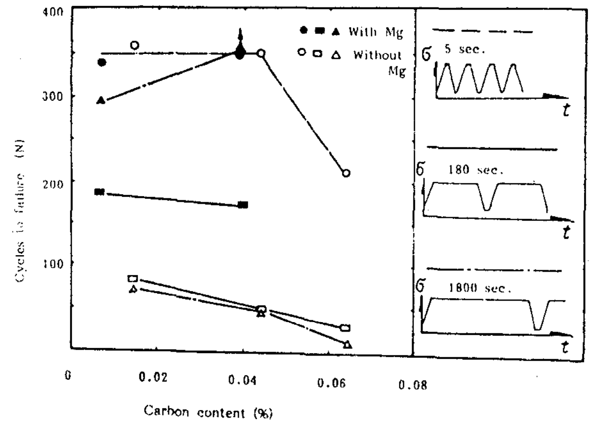


Fig. 7. Carbon effects on notch bar (K_t=3.6) LCF with different dwelling time at maximum stress 686 MPa, 650°C.

The effect of grain size on failure life at different fitigue and creep interaction conditions is illustrated in Figure 8. Figure 8 shows a characteristic fatigue and creep interaction map of fine and coarse grain size (ASTM 8 and 4) notch specimens (Kt = 3.83) on 650°C stress-controlled LCF at maximum stress 900 MPa with different stress ratios (R from -1 to +1). In this map the stress amplitude ($\Delta\sigma$, apparent fatigue stress) and mean stress (σ_m, apparent creep stress) are both plotted on the perpendicular axes in the opposite directions.

Crack propagation rate determination at 650°C stress controlled LCF with different dwelling times shows that fine grain exhibits lower crack propagation rates especially for longer dwelling times at maximum stress. The effect of grain size on crack propagation rate of alloy 718 has been studied by many investigators, but the results are sometimes conflicting. Our fractography and structural analyses show that grain size influence is not only on the geometrical grain dimension but also on the grain boundary precipitates (δ–Ni_3Nb) behavior. Fine grain structure with discrete globular δ–Ni_3Nb particles at grain boundaries exhibits a retardation effect on intergranular crack propagation which decreases crack propagaton rate. Figure 9 shows the effect of grain size on crack propagation at 650°C.

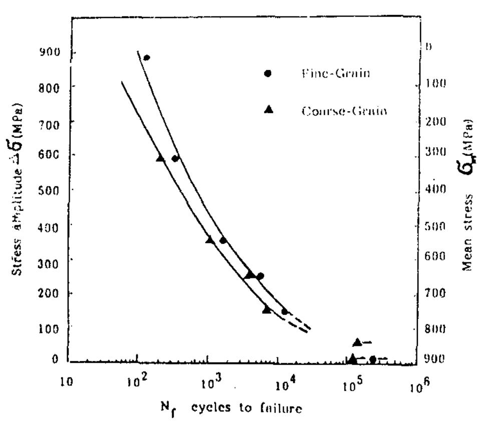


Fig. 8. Grain size effect on fatigue and creep interaction curves at 650°C, maximum stress 900 MPa.

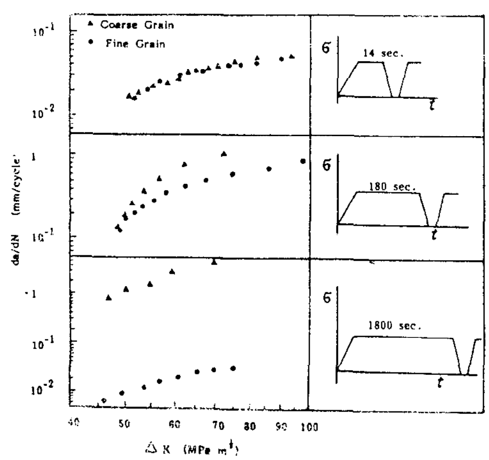


Fig. 9. Grain size effect on crack propagation rates at 650°C stress control LCF with different dwelling times.

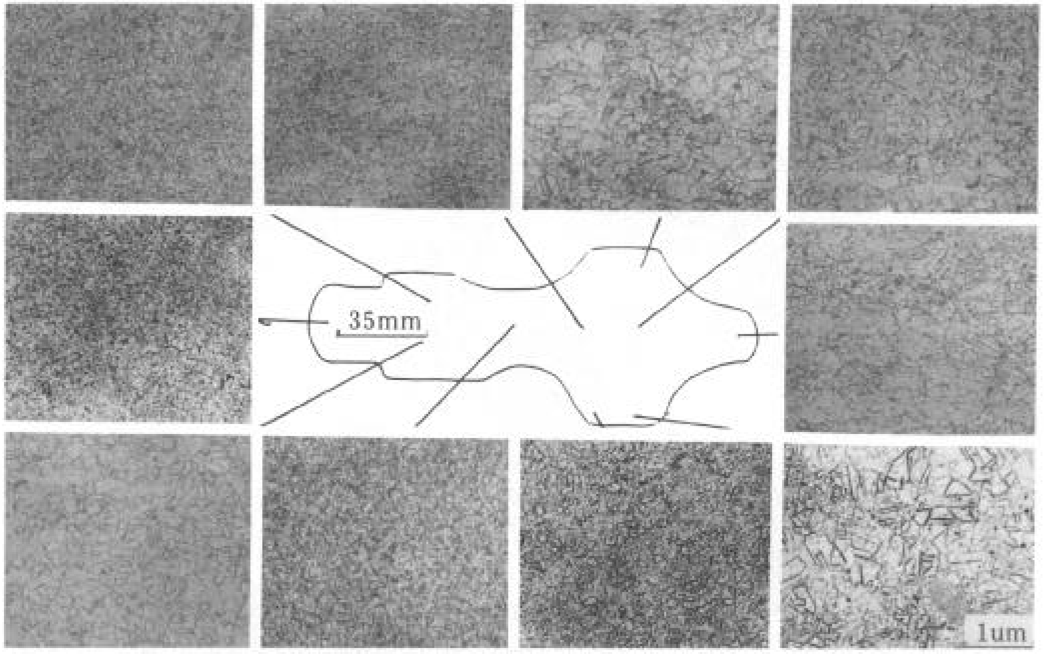
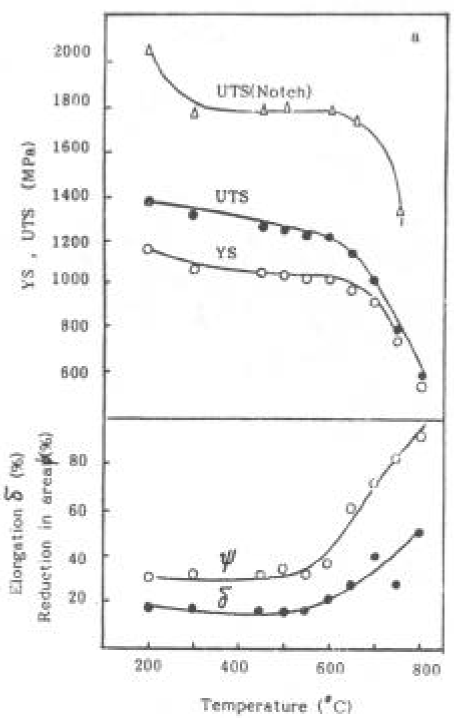


Fig. 10a. Grain structure and microstructure.



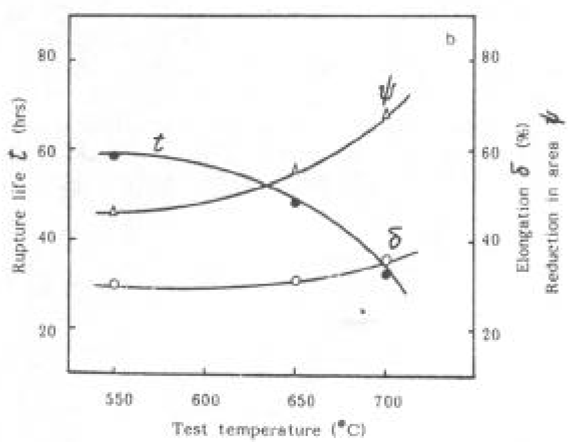


Fig. 11. Tensile (a) and stress rupture (b) properties at different temperature of evaluated alloy 718 disk.

From our fatigue and creep interaction test results and crack propagation rate determination studies, a fine grain structure for alloy 718 disk application was recommended to the forging factories.

Production Disk Evaluation

On the basis of our foregoing recommendations on micro-alloying with Mg, low carbon content and fine grain structures, alloy 718 disks have been produced by several steel plants in China. One of the 435 mm diameter die-forging jet-engine turbine disk from Fushun steel plant was chosen to be cut and tested for material evaluation.

Chemical composition of the evaluated disk (see Table I, Heat 7H21-019) shows the alloy contains low carbon (0.04%), low nitrogen (45 ppm) and is micro-alloyed with 50 ppm Mg. Fine grain structures (average ASTM 8) at different locations of half part of disk are clearly shown in Figure 10a. Structure analyses show the homogeneity of fine discrete globular δ–Ni_3Nb distribution (see Figure 10b). Tensile tests of smooth and notched specimens from 20°C to 800°C, show that the material possesses quite high yield and ultimate strengthes with adequate ductilities (see Figure 11a). Stress rupture properties at 550°C to 700°C also exhibit satisfactory results (see Figure 11b).

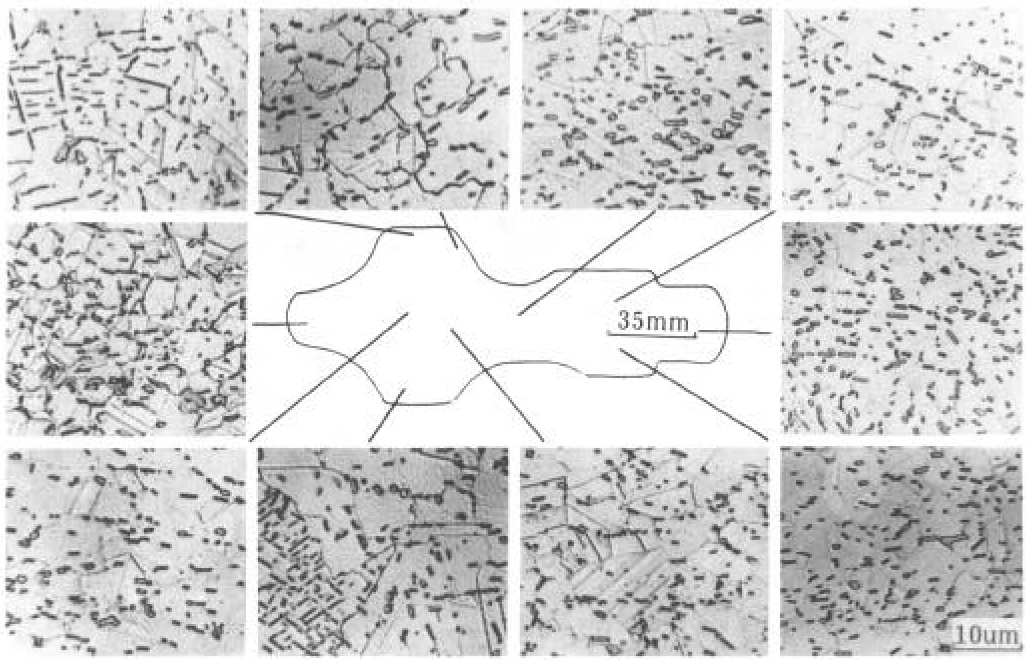


Fig. 10b. Distribution at different locations on half part of 437 mm diameter alloy 718 die-forging disc.

Conclusions

1. The beneficial effects of Mg are found not only on high temperature ductility improvement and creep strengthening property structure improvement in the globular δ–Ni_3Nb distribution at the grain boundaries, and also on solidification and segregation improvement. Mg contents of 40-100 ppm in alloy 718 are recommended for production.
2. High carbon is considered to be deleterious in alloy 718 because of its inclusion contamination; thus, a low carbon content of 0.02 - 0.04% is suggested for this alloy.
3. Fine grain structures provide not only high yield strength and LCF life but also longer life at fatigue and creep interaction conditions. Fine grain structure which have a discrete globular δ–Ni_3Nb distribution at the grain boundaries possess a lower crack propagation rate at stress controlled cyclic loading with longer dwelling times at maximum stress.
4. Low carbon, fine grain (ASTM 8) die-forging disks of alloy 718 with micro-alloying of Mg were successfully produced by several steel plants in China. These disks possessed satisfactory mechanical properties and fulfilled jet-engine requirements.