THE ROLE OF Mg ON STRUCTURE AND MECHANICAL PROPERTIES IN ALLOY 718

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Abstract

The role of Mg in alloy 718 has been systematically investigated. Mg raises not only high temperature tensile and stress-rupture ductilities but also increases considerably smooth and notch stress-rupture life. Mg containing alloy 718M is free of stress-rupture notch sensitivity. Mg improves creep and fatigue interaction properties (LCF or cyclic stress rupture) at any grain size. The basic role of Mg is equilibrium segregation at grain boundaries which helps to change continuous grain boundary δ–Ni_3Nb morphology to discrete globular form which has a retardation effect on intergranular fracture. Mg promotes the change from intergranular to transgranular fracture mode.

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INTRODUCTION

For the past several decades, alloy 718 continues to be used in gas turbines in greater volume and for many applications. High performance demands and high quality requirements expecially in disk application, have required material homogenity, grain size control, and high mechanical properties (such as LCF or cyclic stress rupture) at operating conditions.

In the early 70's Couts et al. [1] studied the effect of Mg (from 1-350 ppm) on mechanical properties of alloy 718 and showed stress rupture ductility improvement in the range of Mg content from 30 to 200 ppm, but little data was presented in the lower content range (up to 100 ppm) of Mg. In 1971 Muzyka et al. [2] showed beneficial stress rupture ductility improvement at 30 ppm Mg in alloy 718. Recently, Moyer [3] in his extra low carbon alloy 718 study showed a remarkable stress rupture ductility and life improvement with a small addition of Mg (13-19 ppm). However, the true effects of Mg have not been fully understood. A systematic research study of Mg effect in nickel- and iron-base superalloys has been conducted in China for a long time [4]. Our previous studies [5,6] show optimum small addition of Mg (less than 100 ppm) not only can increase stress rupture ducitlity but also prolong stress rupture life. The beneficial effect of Mg in alloy 718 can be still maintained even after 5000 hrs long time exposure at 650°C. For further understanding the role of Mg in wrought alloy 718, especially for disk application, an investigation of Mg and grain size effects on structure and mechanical properties, especially on stress rupture notch sensitivity and cyclic stress rupture or LCF was undertaken.

MATERIALS AND EXPERIMENTAL PROCEDURE

Two 79 Kg heats of alloy 718 containing 4 ppm (mg free) and 59 ppm (Mg containing) were VIM melted. Chemical composition and alloy designation are listed in Table I.

Table I. Alloy Chemical Compositions (wt %)

Alloy	C	Mn	Si	P	S	Cr	Fe	Mo	Al	Ti	Nb	B	Mg
718	0.057	0.04	0.23	0.006	0.004	19.10	18.24	2.95	0.68	1.01	4.98	0.0054	0.0004
718M	0.052	0.04	0.23	0.006	0.004	19.04	18.10	2.95	0.67	1.00	4.98	0.0058	0.0059

Alloy ingots were partially homogenized at 1150°C for 6 hours and then forged to produce different grain size experimental disks (ϕ 200 x 45 mm). Typical structure of coarse, fine and mixed grains are shown in Fig. 1.

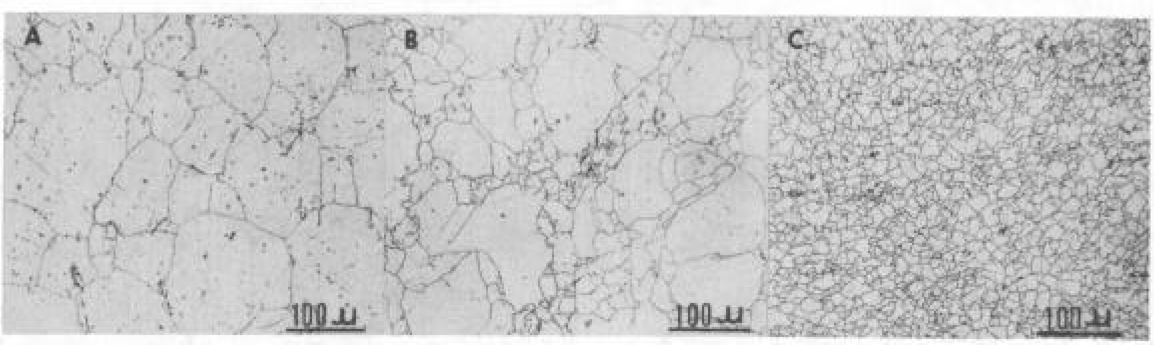

Fig. 1. Typical grain structure of experimental disks with different ASTM grain sizes (after heat treatment); (A) coarse grain, (b) duplex grain, (C) fine grain.

Samples were cut from the rim of disks with different grains sizes and given the ASM 5596C heat treatment, i.e. 950°C/1h/AC +720°C/8h/FC 50°C/h→620°C/8h/AC Mechanical property samples were tensile tested at 650°C, smooth and notched bar stress rupture tested at 650°C/686 MPa, cyclic stress rupture tested at 650°C/686 MPa with different holding times or LCF tested.

Structural characterization techniques included optical, SEM and TEM microscopy, fractography, Auger analysis and X-ray analysis of extracted residues.

EXPERIMENTAL RESULTS

Mechanical Properties

In order to study systematically the grain size and Mg effects on mechanical properties, different grain size disks of Mg free (718) and Mg containing (718M) alloys were made. Different forging procedures were used which produced various amounts of recrystallized and unrecrystalized grains especially in the mixed grain disks. After the ASM 5596°C heat treatment, grain sizes of the experimental disks of the two alloys varied from ASTM 3 to ASTM 10. The mixed grain disks of alloy 718 and 718 M displayed a necklace structure of ASTM 7-8 fine grains surrounded by ASTM 3-4 coarse grains (see Fig. 1).

Results of 650°C tensile tests on all grain size disks showed that Mg can greatly increase ductility but had little effect on ultimate strength, which is only increased by grain refining (see Fig. 2).

Similar to that seen in tensile tests, Mg can remarkably increase the 650°C stress rupture ductility as shown in Fig. 3. It should be noted that Mg not only can increase smooth S/R life but also increase notch S/R life considerably even in mixed grain samples of alloy 718M. Smooth bar S/R tests of mixed grain samples from Mg free alloy 718 disk show only 109 hrs/4.7% elongation, but 176 hrs/20.2% elongation from Mg containing 718M disk. Smooth bar S/R life decreases where notch S/R life increases with finer grain size in Mg free alloy 718. It is clear from Fig. 2 that Mg free alloy 718 will be susceptible to S/R notch sensitivity when grain size is coarser than ASTM 5. A positive advantage of alloy 718M is that Mg increases the notch S/R life remarkably; consequently, Mg containing alloy 718 M is not susceptible to S/R notch sensitivity even at coarse grain and mixed grain conditions. This should be of great benefit for forging of disks.

High temperature LCF or cyclic stress rupture characters are the most important mechanical properties for gas turbine disk application. A study of the grain size and Mg effects on cyclic stress rupture life with different holding times (5, 180, 1800 sec) at maximum stress of 686 MPa/650°C showed that Mg really improved cyclic stress rupture (namely stress controlled LCF with dwelling time) properties at fatigue and creep interaction conditions, representative of disk service conditions.

Microstructure Analyses

Microchemical phase analysis results show that the amount of main strengthening phase of γ'' and γ' phases is not affected by Mg addition or grain size in alloy 718 and 718M as shown in Fig. 5. Mg free alloy 718 or Mg containing alloy 718M both contains approximately 14% $\gamma' + \gamma''$ strengthening phase, independent of grain size. However, δ–Ni_3Nb phase precipitated at grain boundaries increases with grain refinement and amount of Mg. Consequently, the amount of δ–Ni_3Nb is much higher in fine grain alloy 718M as compared to Mg free alloy 718.

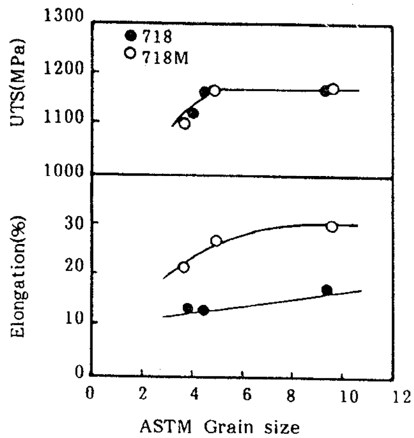

Fig. 2. Grain size and Mg effect on 650°C tensile properties.

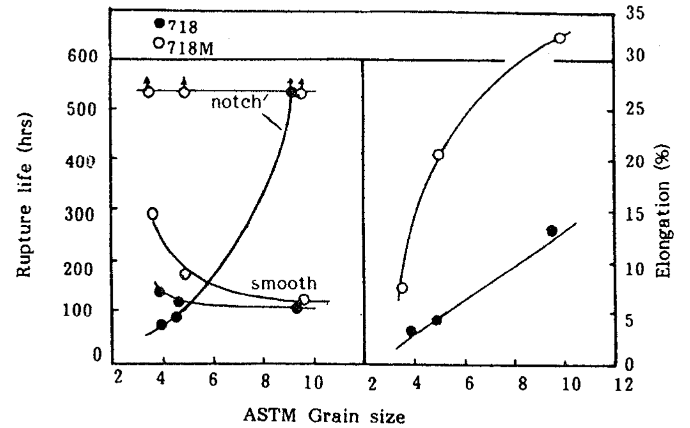

Fig. 3. Grain size and Mg effect on stress rupture life and elongation at 650° C, 686 MPa.

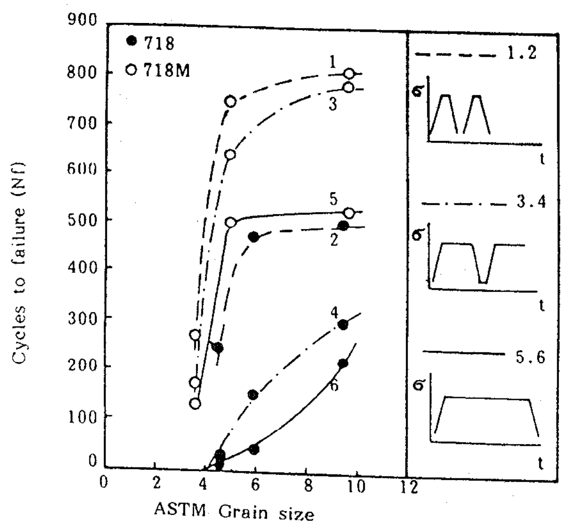

Fig. 4. Grain size and Mg effect on cyclic stress rupture life with different holding times at maximum stress of 686 MPa, 650°C.
1,2-5sec, 3,4-180sec, 5,6-1800sec

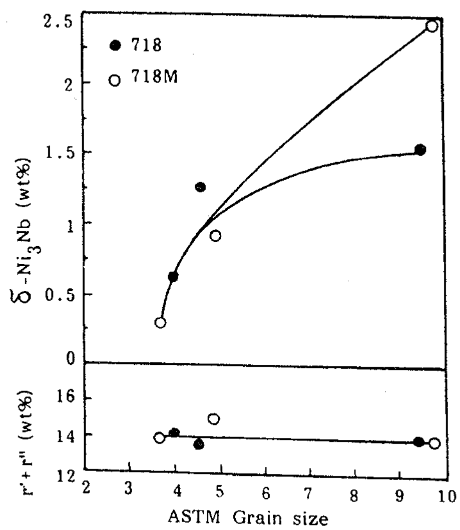

Fig. 5. Grain size and Mg effect on the amount of r'' and σ-Ni_3 Nb.

Mg addition to alloy 718 increases not only δ–Ni_3Nb amount but also changes its morphology from plate-like form to globular and discrete form as shown in Fig. 7 (A and D). Quantitative analysis on the amount of grain boundary δ–Ni_3Nb shows that concentration coefficient of δ–Ni_3Nb at grain boundaries (number of δ particles/wt%δ in certain area) increases with grain refinement because of the increment of total grain boundaries. Mg addition can raise δ–Ni_3Nb concentration coefficient at grain boundaries to a higher level in alloy 718M than in alloy 718 (see Fig. 6). Thus, much smaller and more particles of δ–Ni_3Nb phase appear in Mg containing alloy 718M with fine grain structure.

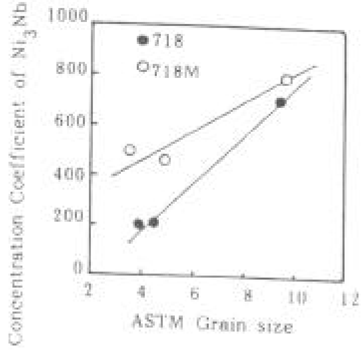

Fig. 6. Grain size and Mg effect on concentration coefficient of N Ni_3Nb at grain boundaries.

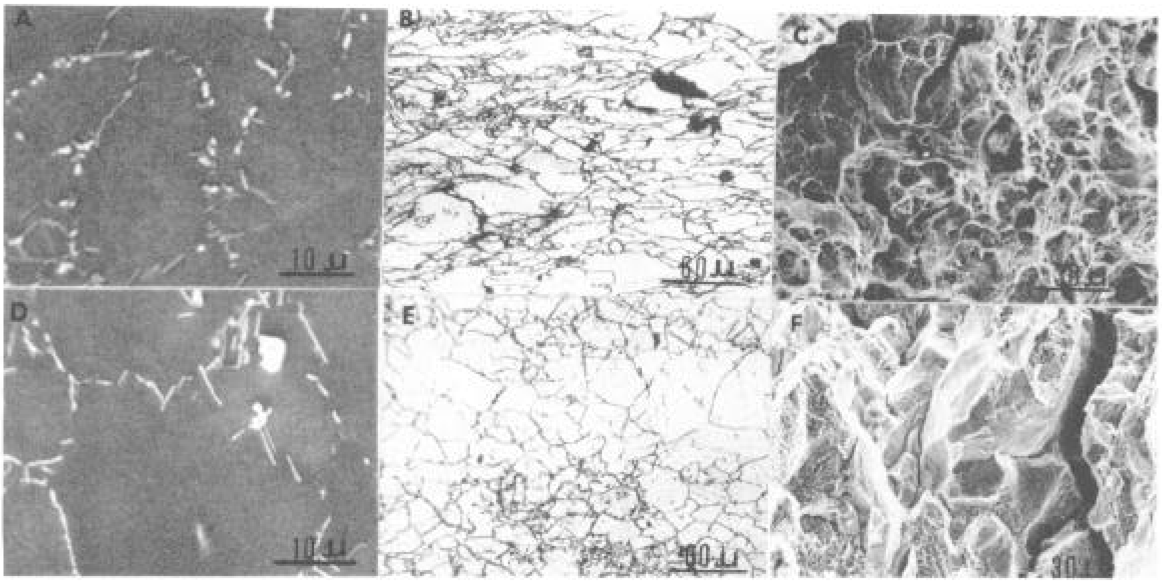

Fig. 7. Mg effect on grain boundary behavior of alloy 718M (A,B,C) and 718 (D,E,F).
A, D - grain boundary Ni_3Nb behavior,
B, E - grain boundary crack behavior,
C, F - intergranular fracture behavior at 650°C, 686MPa.

Fractography Observation

Optical microscopy observation on longitudinal sections of stress rupture samples shows extended elongated grain structure of Mg containing alloy 718M with grain boundary cavities because of high stress rupture ductility (see Fig. 7). In contrast, very small elongation of grains and scarce grain boundary cracks appear in Mg free alloy 718 (see Fig. 7E)

SEM fractographic study of the various grain size stress rupture samples shows that when Mg is present the coarse and mixed grain samples have many more dimples on the intergranular fracture surfaces than in Mg free samples (compare Fig. 7C and F). As the grain size decreases, the intergranular fracture mode changes into a partially transgranular mode. The change from intergranular to transgranular fracture occurs in the mixed grain stress rupture samples of Mg containing alloy 718M while in Mg free alloy 718 transgranular fracture is never totally achieved even in fine grain stress rupture samples.

Auger Analysis

Semi-quantitative Auger analysis on intergranular fracture surface of Mg containing alloy 718M samples shows the profile of Mg content distribution at the grain boundary regions. It can be seen from Fig. 8 that the concentration of Mg at grain boundaries characterizes an equilibrium segregation and Mg has been further concentrated at grain boundaries during long time stress aging time, i.e. Mg content at grain boundaries increases after 526 hrs stress aging at 650°C/686 MPa. After AMS 5596C heat treatment and 526 hrs stress aging conditions, the concentration of Mg decreases gradually away from the grain boundary. The gradual change of Mg content in the region of grain boundary shows that Mg does not exist in grain boundary phases; otherwise, the Mg content would sharply change across the grain boundary.

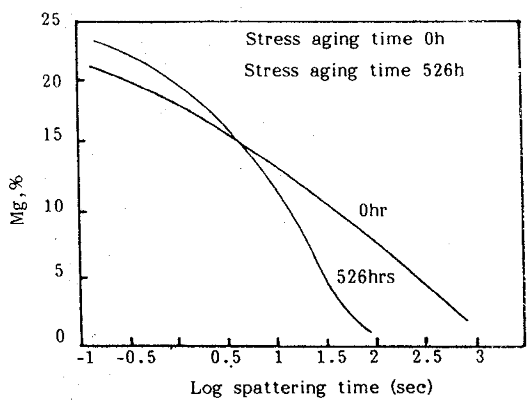

Fig. 8. Grain boundary segregation behavior of Mg in alloy 718M before and after stress aging at 650°C, 686 MPa.

Segregation Effect

Because the degree of Nb segregation remaining after any conversion process results in non-uniform grain sizes and affects the δ–Ni_3Nb solvus temperature, the heat treated samples were given the "TAG" heat treatment [7] to detect residual segregation of Nb. It was found that the Mg containing alloy 718M samples appear to have less segregation than Mg free alloy 718.

DISCUSSION

The great advantage of adding Mg to alloy 718 is that Mg can greatly increase 650°C tensile and stress-rupture ductility and also increase smooth and notch stress-rupture lives remarkably. Mg containing alloy 718M is free from stress-rupture notch sensitivity, which is important for material used for disk application. In addition, another benefit of Mg addition in alloy 718 is that Mg improves creep and fatigue interaction properties (LCF or cycle stress-rupture), so necessary for turbine disk applications.

The diffusion to and segregation of Mg at grain boundaries changes grain boundary behavior. Magnesium addition can change grain boundary precipitation of δ–$Ni_{13}Nb$ from continuous plate-like form to discrete globular shapes, and retards intergranular crack growth as schematically shown in Fig. 9. This grain boundary precipitation behavior was also confirmed in nickel-base [5] and iron-base superalloys [8]. The amount of δNi_3Nb precipitation at the grain boundaries depends on grain size, amount of Mg, and heat treatment.

Because Mg is concentrated at the grain boundaries, Mg cannot severely affect precipitation behavior in bulk grains. As a result, the amount of strengthening phase ($\gamma' + \gamma''$) in grains is not affected by Mg addition in alloy 718 and is nearly constant ($\sim 14\% \ \gamma' + \gamma''$) in both alloy 718 and 718M at all grain sizes.

Concentration of Mg at grain boundaries plays a strengthening role on grain boundaries. It allows more deformation in bulk grains before intergranular fracture occurs in stress-rupture tests. From the viewpoint of creep, Mg prolongs the secondary creep stage and develops a tertiary creep stage in nickel-base and iron-base superalloys [8] which should raise both stress rupture ductility and failure life. Ductile stress-rupture fracture surfaces with much more dimples should appear in Mg containing alloy 718M samples.

It appears Mg can reduce the Nb segregation in cast alloy 718 ingots which allows for material homogenity improvement during conversion practice. Detail study of Mg effect on segregation behavior will be discussed in other papers [9].

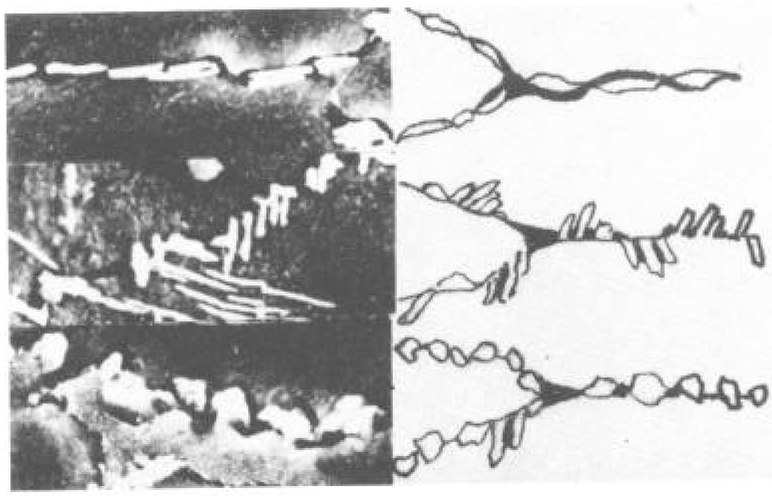

Fig. 9. Grain boundary σ-Ni_3Nb behavior and intergranular crack propagation mode suggested.

CONCLUSIONS

1. Mg increases 650°F tensile and stress-rupture ductilities remarkably but has little effect on tensile strength; however, the smooth and notch stress-rupture lives both increase considerably and Mg containing alloy 718 M is free of stress-rupture notch sensitivity at any grain size.
2. Mg improves 650°C creep and fatigue interaction properties (LCF or cyclic stress-rupture) at any grain size.
3. Mg does not appear to have effect on the wt.% of strengthening phase ($\gamma' + \gamma''$). However, the wt.% of δ–Ni_3Nb is much greater in fine grain alloy 718M indicating that Mg affects the precipitation of δ–Ni_3Nb at grain boundaries.
4. Mg plays a role of equilibrium segregation at grain boundaries and changes grain boundary δ–Ni_3Nb morphology from continuous plate-like form to discrete globular shapes, producing a retardation effect on intergranular fracture which simultaneously increases stress-rupture ductility and prolongs failure life.

5. Mg can produce ductile stress rupture fracture and hasten the change from intergranular fracture mode into partially transgranular mode.
6. Mg may appear to be beneficial to improve Nb segregation in alloy 718.

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