EFFECT OF HEAT TREATMENT AND COMPOSITIONAL MODIFICATION ON STRENGTH AND THERMAL STABILITY OF ALLOY 718

Encai Guo, Fengqin Xu and E.A. Loria

Central Iron & Steel Research Institute
Beijing, China

and

Niobium Products Company
Pittsburgh, Pennsylvania, U.S.A.

Abstract

The strength of Alloy 718 must be improved beyond 650°C in order to meet the design needs for advanced aeroengines. A recent series of papers show particular promise via minor compositional modifications. Two modified 718 alloys that do so utilizing the standard 718 heat treatment were given heat treatments that changed the morphology of the coexisting γ'/γ'' precipitates as a possible way of producing an additional improvement in mechanical properties. Tensile test results at room temperature and stress rupture life at 700°C and 638 MPa (92.5 ksi) are presented which led to the selection of a heat treatment which provided superior properties in each case for the sequel study.

Introduction

The recent series of papers[1–5] modifying the chemical composition of Alloy 718 has shown that mechanical properties beyond 650°C can be improved with either the non-compact or the compact γ'/γ'' precipitate morphology obtained by appropriate heat treatment. The former is the conventional mixture of disk-shaped γ'' and round γ' particles plus γ'' bound to γ' particles, thereby forming, to some degree, a hemispherical shape. The latter consists entirely of cuboid-shaped γ' particles coated with a shell of γ'' particles. In our initial study employing the standard 718 heat treatment,[1] which produced the conventional precipitate structure, four of our modified alloys produced superior hardness and tensile properties up to 534 hr at 730°C plus the improvement in 100 hr stress rupture life shown in Figure 1. Microstructurally, a slower rate of γ'' coarsening along with a larger γ' size and smaller γ'' length was observed which could mean that more γ' was produced while stabilizing the γ'' phase at the same time.

With the existence of both the γ' and γ'' phases in Alloy 718, it is tempting to consider heat treatments for a modified composition that would produce a greater amount of γ' phase in order to increase high temperature strength (in particular creep resistance). In contrast to the bct crystal structure of the γ'' phase, the much

Superalloys 718, 625 and Various Derivatives
Edited by Edward A. Loria
The Minerals, Metals & Materials Society, 1991

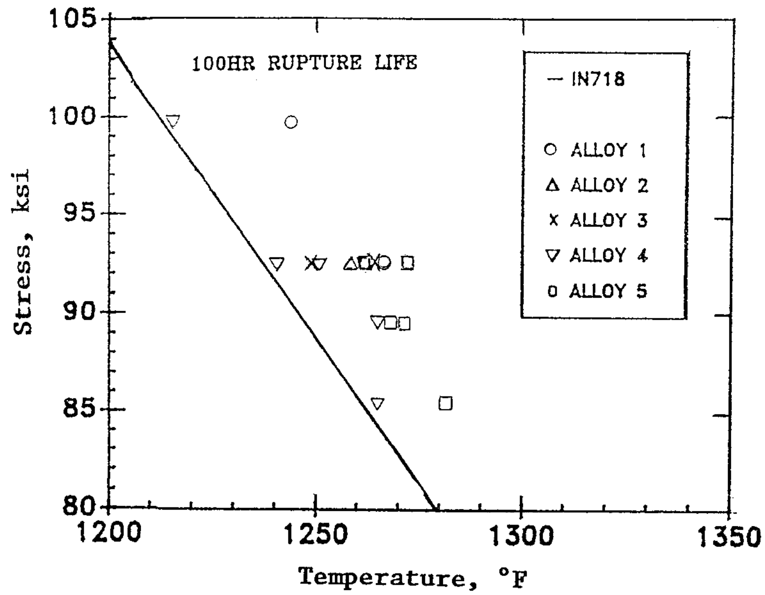

Figure 1 – Conversion of stress rupture data for Alloys 1 to 5 to 100 hour rupture life via the Larson-Miller parameter (C=22) compared to trend-line established for Super 718.

closer lattice parameter match between the fcc γ' and the fcc γ matrix results in greater thermodynamic stability of the precipitate phase and translates into reduced tendency towards precipitate coarsening and thus greater elevated temperature strength. The morphological change of the γ' particles would be strongly influenced by the lattice match between the γ' and γ phases; therefore, the optimum heat treatment temperature would vary depending on lattice mismatch. For a modified alloy with a larger lattice mismatch, a lower temperature heat treatment would be desirable whereas for alloys with smaller mismatch a higher heat treatment temperature would be necessary. Also, a heat treatment for an appropriate composition that produces a partially compact or a complete compact γ'/γ'' precipitate structure[5] should be studied as the latter has shown attractive strength and thermal stability above 650°C. With this in mind, the effects of various heat treatments on the mechanical properties of two modified 718 alloys from our initial study are reported.

Materials and Procedure

The two modifications of Alloy 718 employed in this study were produced as 5 kg or 23 kg ingots from VIM heats and given the initial processing previously described.[1] Their chemical compositions taken from hot forged 32mm bars are listed in Table I. Appropriate specimens were cut from these bars and given the heat treatments listed in Table II, and several hardness measurements were made on the cross section of each specimen. Hardness tests (Rc) were used as an economical indicator of mechanical strength and appropriate heat treatment for each alloy. Tensile and stress rupture tests followed standard procedures and were made at room temperature and at 700°C under 638MPa (92.5 ksi). For each heat treatment, thin foils were prepared and observed by transmission electron microscope. The γ' and γ'' phases were identified using electron diffraction and dark field techniques with (001) axis of the matrix parallel to the electron beam.

Table I Chemical Composition of Alloys wt.%

Alloy	C	Cr	Mo	Ti	Al	Nb	Fe	W	B
3	0.056	17.58	2.85	0.97	0.86	5.51	17.00	--	0.0033
5	0.048	16.60	3.09	0.98	0.93	5.57	13.71	2.30	0.0019

Table I. Chemical Composition of Alloys at.%

Alloy	Cr	Mo	Ti	Al	Nb	Fe	W	Ni	Al+Ti+Nb	Al/Ti	Al+Ti/Nb
3	19.60	1.72	1.18	1.85	3.44	17.65	--	54.90	6.47	1.57	0.88
5	18.87	1.90	1.21	2.04	3.55	14.52	0.76	57.14	6.80	1.69	0.92

A number of heat treatments have been proposed to improve a specific property or to optimize a combination of properties. The grain size that develops as the result of solutioning the other microstructural variables, the δ morphology and the γ′/γ″ precipitates are very important relative to ambient strength and rupture life at elevated temperatures. Our solutioning treatments of 1 hour at 980°C or 1030°C produced a grain size of ASTM6–7 and ASTM5–6 respectively and ASTM4–5 for the single 1050°C treatment. Koul et al[6] have shown that grain coarsening occurs only above 1030°C when 1 hour treatments are employed, and this solution temperature was optimum for full solutioning of the above phases without inducing grain growth. Also, it should be noted that air cooling was employed after the solution anneals between 955°C and 1050°C. Onyewuenyi[7] has shown that there can be a variation in hardness with the rate of cooling from the annealing temperature but it is not significant above 980°C while at 955°C the hardness upon air cooling is equivalent to the value for a slow cooling in vermiculite. Finally, the selection of these temperature affects the age hardening response obtained by the selection of the double aging temperatures.

Results

Employing the conventional solution treatment of 955°C for 1 hour and air cooling of the initial study, the effect of increasing the first stage aging temperature to 750, 770 or 790°C for 8 hours and then air cooling was to maintain the hardness

Table II List of Heat Treatments for Alloys 3 and 5

Alloy	Code	Heat Treatment Sequence
3	A	955°C/1hr, AC, 720°C/8hr, 50°C/hr FC to 620°C/8 hr, AC
	B	1030°C/1hr, AC, 720°C/8hr, 50°C/hr FC to 620°C/8hr, AC
	C	980°C/1hr, AC, 800°C/1hr, 50°C/hr FC to 650°C/16 hr, AC
	D	980°C/1hr, AC, 850°C/1hr, 50°C/hr FC to 650°C/16hr, AC
	E	980°C/1hr, AC, 800°C/1hr, AC, 650°C/8hr, AC
5	A	955°C/1hr, AC, 720°C/8hr, 50°C/hr FC to 620°C/8hr, AC
	B	1030°C/1hr, AC 720°C/8hr, 50°C/hr FC to 620°C/8 hr, AC
	C	1050°C/1hr, AC, 800°C/1hr, AC, 650°C/8hr, AC
	D	1030°C/1hr, AC, 850°C/1hr, 50°C/hr, FC to 650°C/16hr, AC
	E	1030°C/1hr, AC, 800°C/1hr, AC, 650°C/16hr, AC
	F	1030°C/1hr, AC, 720°C/8hr, 50°C/hr FC to 650°C/16hr, AC
	G	1030°C/1hr, AC, 800°C/1.5hr, 50°C/hr FC to 650°C/16hr, AC

AC Signifies Air Cooled and FC Signifies Furnace Cooled

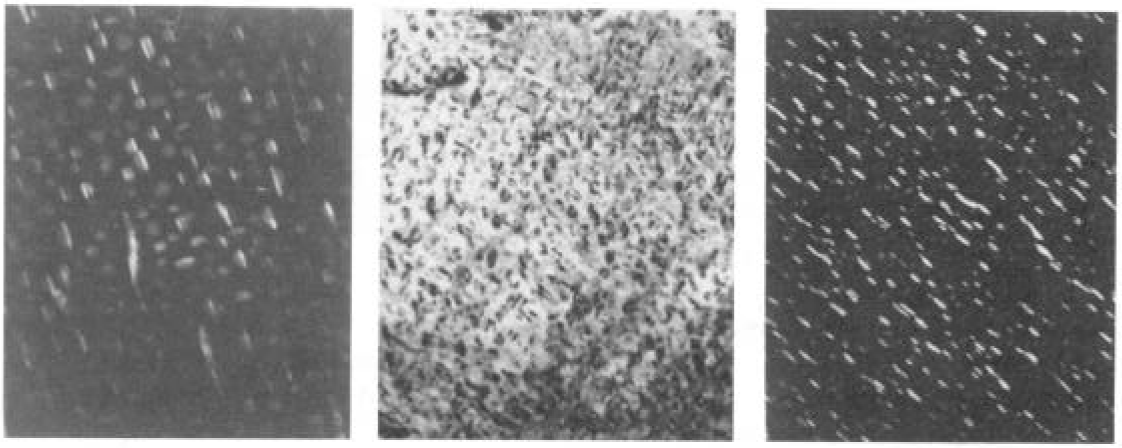

Figure 2. Transmission electronmicrographs on increasing primary aging temperature from 750 to 790°C after 955°C solution treatment. (a) Alloy 3, 790°C, dark field, X60000. (b) Alloy 5, 750°C, bright field, X60000. (c) Alloy 5, 790°C, dark field, X37000.

of alloy 3 at Rc40 between 750 and 770°C. It then decreased to Rc36.5 after aging at 790°C. The hardness of Alloy 5 decreased in a straight-line from Rc40 to Rc39 to Rc38 for the three temperatures. As seen in Figure 2 raising the primary aging temperature from 750°C to 790°C still produced the conventional non-compact precipitate structure and these results led to the consideration of even higher first stage aging treatments coupled with higher solution temperatures.

In the case of Alloy 3, a solution temperature of 980°C, coupled with an increasing first stage aging temperature between 750 and 850°C, and then secondary aging at 650°C for 8 hours, produced a rising hardness from Rc45.5 to almost Rc48, per Figure 3. Increasing the solution temperature to 1010° or 1030°C did not achieve these hardness values. The next best Rc46 hardness was obtained with a 1030°C solution treatment and 800°C first stage aging treatment, while a solution treatment at 1010°C and 850°C first stage aging treatment reached about Rc45.5. The use of a lower second stage aging at 620°C produced inferior hardness in both cases. Also, it should be noted that a hardness of Rc41 to 42.5 was obtained when a lower first stage age at 750°C was used in these treatments, compared to Rc45.5 for the 980°C solution temperature. Transmission electron micrographs, Figure 4, revealed that a partial compact γ'/γ'' precipitate structure was obtained with heat

Table III Mechanical Properties of Alloy 3 after Heat Treatment

	Grain	Tensile Test Results at 25°C						Stress Rupture*			Hard
	Size	0.2% Yield		Ultimate		El	RA	Life	El	RA	ness
Code	ASTM	MPa	ksi	MPa	ksi	%	%	hr	%	%	Rc
A	8	1020	147.9	1360	197.3	26	37				48.5
		1010	146.5	1340	194.4	22	31				
B	5							26.8	23.6	49.7	
								38.7	8.0	19	
C	7	1175	170.4	1500	217.6	20	36	35.5	21	33.5	48
D	7	1150	166.8	1525	222.6	18	31	23.3	10.6	14.6	47
E	7	1145	166	1510	219	20	40	16	7.8	11.2	47.5
		1160	168.2	1515	219.7	19	41	10	5	11.1	

*Stress rupture testing at 700°C (1300°F) under 638 MPa (92.5 ksi)

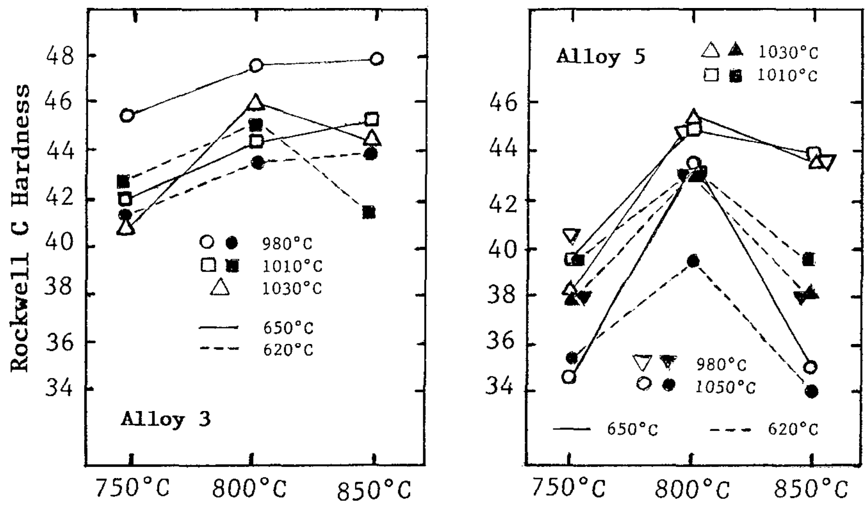

Figure 3 - Hardness variations in Alloy 3 and 5 after the heat treatments listed in Table II.

treatment C and a compact γ'/γ'' precipitate structure was obtained with heat treatment D.

Mechanical properties for Alloy 3 employing the specified heat treatments are presented in Table III. In room temperature tensile tests, higher yield and ultimate strength were obtained with the optimum being a trade-off between heat treatments C and D. Hence, one would conclude that the difference between the partially compact and the compact γ'/γ'' precipitate structure produced by these heat treatments, per Figure 4, provided no difference in room temperature strength of Alloy 3. On the other hand, stress rupture life at 70°C under 638 MPa (92.5 ksi) was significantly longer at 35.5 hours for the former compared to 23.3 hours for the latter which is somewhat surprising. This will be verified by additional testing in the sequel study. Also, it should be noted that the stress rupture results for these heat treatments are equivalent to those obtained for heat treatment B utilizing a higher (1030°C) solution treatment and lower first stage aging temperature. The coarser grain size of heat treatment B (ASTM5 vs 7) would be expected to improve rupture life.

As seen in Figure 3, increasing the solution temperature between 980°C and 1030°C in Alloy 5, coupled with a primary aging at 800°C and secondary aging at 650°C, produced a maximum hardness of Rc45 and it dropped gradually to Rc43.5 when the primary aging temperature was raised to 850°C. Increasing the solution temperature to 1050°C produced a wide variation with a maximum Rc43.5 at 800°C while the use of a lower secondary aging at 620°C produced a similar variation with inferior hardness compared to the values obtained with the 650°C treatment. Transmission electron micrographs, presented as Figure 5, revealed that coarser γ'' particles were obtained for the 1030°C and 850°C aging treatment D compared to the lower 800°C aging treatment G which produced smaller, closely spaced γ'' particles with smaller, barely resolvable γ' particles. These results led to the selection of either a 1030°C or 1050°C solution treatment coupled with an 800°C or 850°C first stage aging (heat treatments D and G) for the determination of mechanical properties.

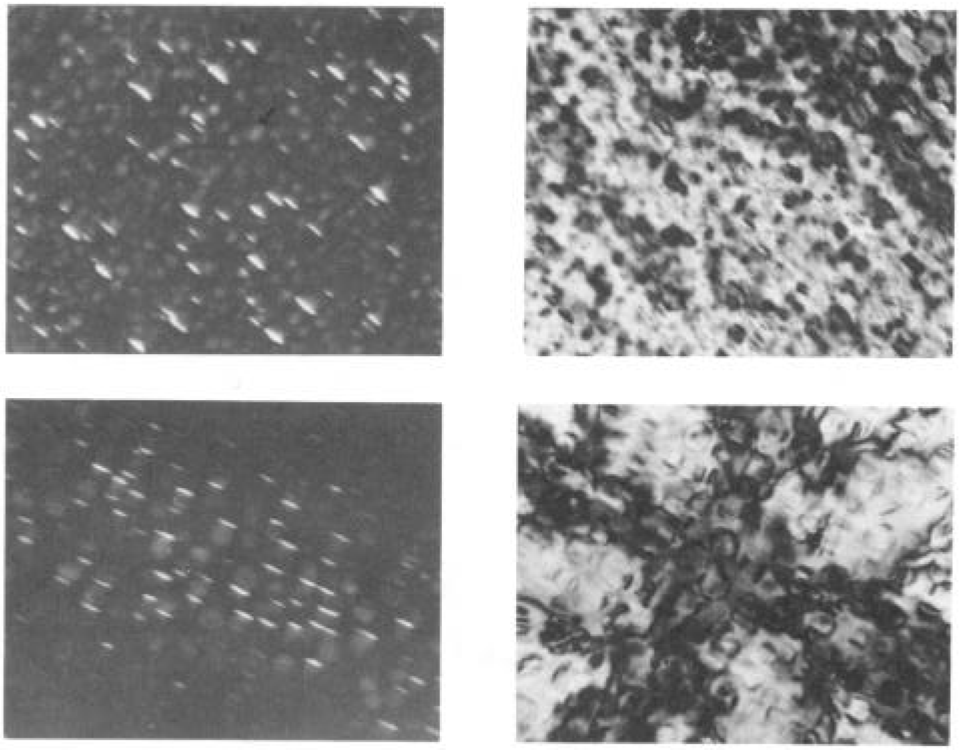

Figure 4. Transmission electronmicrographs of Alloy 3. (a,b) Partial compact γ'-γ'' precipitates after heat treatment C. (c,d) Compact γ'-γ'' precipitates after heat treatment D. Dark and bright field X80000.

In Table IV, the mechanical properties of Alloy 5 employing heat treatments C to G are compared with these obtained previously with the standard 718 heat treatment . Both higher yield and ultimate strength in tensile tests at room temperature were obtained with the new heat treatments, with the highest values evident for D and G employing the 1030°C solution treatment with primary aging at 800°C or 850°C and longer secondary aging at 650°C. It is noteworthy that the values obtained for a coarser ASTM5–6 are even higher than those obtained with a

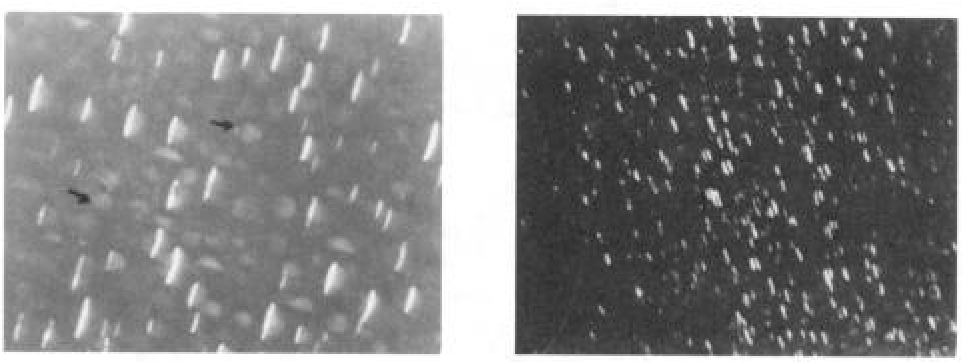

Figure 5. Transmission electronmicrographs of Alloy 5. (a) Partial compact γ'-γ'' precipitates after treatment D and (b) after treatment G. Dark field, X80000.

Table IV Mechanical Properties of Alloy 5 after Heat Treatment

Code	Grain Size ASTM	Tensile Test Results at 25C 0.2% Yield MPa	ksi	Ultimate MPa	ksi	El %	RA %	Stress Rupture* Life hr	El %	RA %	Hard-ness Ro
A	8-9	950	137.8	1310	190	25	47				46
		970	143.6	1330	192.9	29	46				
B	5-6							40.1	13.6	50.2	
C	4-5	1030	149.4	1370	198.7	24	49	36.8	5.3	7.1	43.5
		1070	155.2	1385	200.9	24	49	28.3	5.1	11.8	
D	5-6	1075	155.9	1455	211.0	21	35	31.7	4.5	7.5	
E	5-6	1090	158.1	1395	202.3	26	42	22.8	4.3	6.9	45.4
F	5-6	930	134.9	1350	195.8	31	46	21.3	9.7	18.6	
G	5-6	1110	161.0	1485	215.4	22	37	30.4	6.4	11.2	

*Stress rupture testing at 700°C (1300°F) under 638 MPa (92.5 ksi)

finer ASTM8–9 grain size obtained via the lower 955°C solution temperature of treatment A. On the other hand, on an equivalent grain size basis, the stress rupture life values for the new heat treatments are somewhat lower than originally. In our sequel study, more data will be obtained to establish average values for heat treatment G which has been selected at the best way to produce a fine noncompact γ'/γ'' precipitate structure in Alloy 5.

Alloy 3 and Alloy 5 have essentially the same base composition except for an addition of tungsten to provide a solid solution strengthening effect in Alloy 5. Ambient tensile yield and ultimate strength of both was improved in all heat treatments when compared with the standard 718 heat treatment. The result obtained with the lower solution temperature for Alloy 3 (980°C, finer ASTM7 grain size) produced slightly higher values than those obtained with the higher solution temperature on Alloy 5 (1030°C, ASTM5–6 grain size), except that heat treatment G for Alloy 5 provided equivalent values. Also, this heat treatment and grain size provided an improvement in the time to rupture at 700°C and 638MPa. Heat treatment G for Alloy 5 was selected on the premise that a longer primary aging time may improve grain boundary plasticity to elevate stress rupture and elongation and a longer secondary aging time may elevate strength.

References

1. E. Gou, F. Xu and E.A. Loria, *Superalloy 718: Metallurgy and Applications*, TMS (1989), pp. 567–576.

2. J.P. Collier, S.H. Wong, J.C. Phillips and J.K. Tien, *Metall. Trans.*, 19A (1988), pp. 1657–1666.

3. J.P. Collier, A.O. Selius and J.K. Tien, *Superalloys 88*, TMS (1988), pp. 43–52.

4. R. Cozar and A. Pineau, *Metall. Trans.*, 4 (1973), pp. 47–59.

5. E. Andrieu, R. Cozar and A. Pineau, *Superalloy 718: Metallurgy and Applications,* TMS (1989), pp. 241–256.

6. A.K. Koul, P. Au, N. Ballinger, R. Thamburaj, W. Wallace and J.P. Immerigeon, *Superalloys 88,* TMS (1988), pp. 3–12.

7. O.A. Onyewuenyi, *Superalloy 718: Metallurgy and Applications,* TMS (1989), pp. 345–362.