IMPROVING STRESS RUPTURE LIFE OF ALLOY 718 BY OPTIMIZING AL, TI, P AND B CONTENTS

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Abstract

An attempt was made to combine the beneficial effects of P and B with modifications of Al, Ti and Nb to improve stress rupture properties of alloy 718. Three versions of Al, Ti and Nb modifications suggested in the literature; 718Ti/Al with higher Ti and Al (1.35Ti, 0.65Al), Ticolloy with higher Al (1.0Ti, 1.0Al) and alloy 718CM with compact morphology of γ'' and γ'' (1.25Ti, 1.10Al, 5.0Nb) were selected for investigation. Standard 718 (1.0Ti, 0.5Al) was also made as a base for comparison. Each group of alloys was melted at three P and B levels: (0.006P, 0.004B), (0.002P, 0.004B) and (0.020P, 0.010B). Mechanical properties of each alloy, including tensile at room and elevated temperature and stress rupture properties, were determined.

The results from standard alloys confirmed previous studies. The increased P and B led to a 60 to 90% improvement in stress rupture life with tensile strength being unchanged. The effect of modified strengthening elements on mechanical properties at standard P and B level was consistent with data published in the literature. Stress rupture life of alloy 718 was moderately increased by strengthening element modifications in the standard heat treatment condition. Tensile strength was generally not affected or slightly reduced. The principal effect of modified strengthening elements was to increase thermal stability. Combining high P and B levels with Al, Ti and Nb modifications resulted in a further improvement in stress rupture properties and this improvement was maintained to higher temperature and after long time thermal exposure. Alloy 718CM with increased P and B levels showed the best results. Combining the modifications used in this study moderately improved the temperature capability of alloy 718.

Superalloys 718, 625, 706 and Various Derivatives
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Introduction

Many attempts have been made to improve the elevated temperature properties of alloy 718 by chemistry modification, including changes in both major and minor chemical elements.

Previous studies by the authors [1-5] have demonstrated that the minor element P has a dramatic effect on the elevated temperature creep and stress rupture properties of alloy 718. As shown in [1], increasing P from about 0.006%, typical of standard commercial 718, to 0.02% can result in nearly a 100% increase in stress rupture life at 650°C. The positive effect of increased P contents has been supported by many subsequent studies [6-11]. It has also been shown [2,3] that there is a synergic effect between P and B, and increased P combined with increased B can further improve creep and stress rupture properties of alloy 718. Low C in combination with increased P and B contents can increase stress rupture life at 650°C by as much as 200-300% at the optimum combination of 0.022% P, 0.011% B and 0.005% C. A similar synergic effect of P and B applies to creep properties of alloy 718 [5, 12, 13]. However, recent work [14] has shown that the P and B modification does not noticeably improve the thermal stability of alloy 718, and that the improvement in creep and stress rupture properties diminished with increasing test temperature and after long time thermal exposure at elevated temperature.

Many attempts have been made to modify the major strengthening elements Nb, Ti and Al in alloy 718 to improve its performance at elevated temperature. One approach has been to increase Al/Ti ratio and/or (Al+Ti)/Nb ratio to reduce the coarsening rate of γ'' particles and to retard the formation of δ phase at elevated temperatures [15-18]. This direction led to the development of Ticolloy containing about 1% Al and 1% Ti [17, 18]. Another idea was to closely control the (Al+Ti)/Nb ratio and the (Al+Ti+Nb) sum such that a specific $\gamma' + \gamma''$ microstructure, termed "compact morphology", was achieved [19-21]. This consisted of cube-shaped γ' particles coated with a shell of γ'' precipitates which were very stable at elevated temperatures. The mechanical properties of alloy 718 with modified Al, Ti and Nb contents have been evaluated in a number of additional studies [22-26]. The improvement in elevated temperature properties was relatively small, especially after taking grain size effects into account. The increase in stress rupture life was less than 25% in most cases. However, the thermal stability of alloys did increase, as shown by less reduction in stress rupture life after long time heating at elevated temperatures.

A natural development for further improving elevated temperature properties of alloy 718 would be to combine both the major and minor element approaches. The goal would be to maintain the improvement in creep and stress rupture properties from P and B modification to higher temperature by virtue of Al, Ti and Nb modifications and, therefore, increase the temperature capability of alloy 718. This paper will report the results of research performed at Allvac along this direction.

Experimental Procedures

Test Materials and Processing

Chemistries of the alloys prepared for this study are listed in Table I. All were basically identical except for strengthening elements (Al, Ti and sometimes Nb), and minor elements (P and B and in one case C). The alloys were divided into four groups on the basis of Al, Ti and Nb levels: standard 718 with 1.0% Ti, 0.5% Al (group 1), 718Ti/Al with 1.35% Ti, 0.65% Al (group 2), Ticolloy with 1.0% Ti, 1.0% Al (group 3) and 718CM (compact morphology) with

1.25% Ti, 1.1% Al, 5.0% Nb (group 4). Three P and B levels were produced in each group. The 0.008% P, 0.005% B levels are close to P and B contents of commercial 718. Increased P and B levels (0.020% P, 0.010% B) have been shown to achieve optimum creep-stress rupture properties in standard 718. Alloys with 0.002% P were included to show the effect of low P content.

Table I. Chemistries of Test Alloys with Modified Al, Ti, P and B

Heat No.	Chemistry (wt.%)								
	C	Mo	Cr	Fe	Nb	Ti	Al	Mg	P*	B*
Group 1: Standard 718 (0.5% Al + 1.0% Ti)										
WD83	0.028	2.87	17.9	18.1	5.45	1.00	0.53	10	20	37
WE87	0.031	2.90	17.8	18.1	5.47	0.99	0.52	14	80	60
WD84	0.032	2.88	17.9	18.0	5.47	1.00	.0050	10	200	103
WE91	0.006	2.89	17.8	18.1	5.46	1.00	0.54	14	210	100
Group 2: 718Ti/Al (0.65% Al + 1.35% Ti)										
WD86	0.027	2.88	17.9	17.9	5.45	1.35	0.65	12	20	31
WE89	0.028	2.88	17.8	17.7	5.46	1.34	0.69	18	90	50
WD85	0.030	2.87	17.9	17.8	5.44	1.35	0.66	15	200	100
Group 3: Ticolloy (1.0% Al + 1.0% Ti)										
WD91	0.028	2.90	18.0	17.9	5.51	1.01	0.96	16	20	36
WE88	0.033	2.88	17.9	17.8	5.42	1.00	0.98	16	80	50
WD88	0.026	2.90	17.9	17.9	5.49	1.00	0.94	16	210	114
Group 4: 718CM (1.10% Al + 1.25% Ti)										
WD90	0.028	2.89	18.0	18.0	4.95	1.23	1.09	23	20	35
WG45	0.027	2.91	18.0	17.9	5.08	1.24	1.09	19	80	50
WD89	0.028	2.90	18.0	18.0	5.01	1.24	1.11	17	210	102

* Contents in ppm.

The melting and hot working of test alloys were the same as those used in previous studies [1-5]. Briefly, all were vacuum induction melted (VIM) and vacuum arc re-melted (VAR) to 100 mm diameter ingots with a weight of 23 Kg. Ingots were homogenized for 16 hrs. and rolled to 15 mm diameter bars within a temperature range of 1040°C to 920°C.

All alloys were subjected to the solution heat treatment of 954°C x 1 hr., air cooled and then aged at 718°C x 8 hrs., furnace cooled at 55°C/hr. to 621°C, held for 8 hrs., air cooled, typical for standard 718. Modified heat treatments suggested in the literature [18,26] to fully utilize the beneficial effect of modified strengthening elements were also used. Alloys Ticolloy and 718Ti/Al were heat treated at 982°C x 1 hr. solution, air cooled and then aged for 8 hrs. at 760°C, furnace cooled at 55°C/hr. to 649°C, held for 8 hrs., air cooled. For 718CM, the modified heat treatment was 982°C x 1 hr. solution, air cooled and then aged for 1/2 hr. at 850°C, furnace cooled at 200°C/hr. to 649°C, held for 16 hrs., air cooled. Alloy 718 was also tested with a 982°C solution + standard age treatment to determine the effect of chemistry modifications without the interference of grain size differences. Samples subjected to the modified heat treatments were further heat treated at 704°C for 1000 hrs. to evaluate thermal stability.

Mechanical Tests

Two slightly different series of mechanical tests were carried out on the two different heat treatment conditions: room temperature tensile, 649°C tensile, and stress rupture tests at 649°C/

669 MPa and 649°C/773 MPa on alloys subjected to the standard heat treatment: room temperature tensile, 649°C tensile and stress rupture tests at 677°C/690 MPa and 704°C/621 MPa on alloys given the modified heat treatments. This latter series of tests was performed on samples, both as-heat treated and after 1000 hrs. exposure at 704°C. Higher test temperatures were used in this second series of tests to better evaluate the temperature capability of alloy 718 with modified chemistries. All test results represent the average of at least two tests.

Microstructures

Microstructures after different heat treatments were examined by optical and scanning electron microscope (SEM). No attempt was made to characterize the precipitates by transmission electron microscope (TEM) since this work had been performed in detail by other researchers. Emphasis was placed on the study of grain size, δ phase particles and microstructure after 704°C x 1000 hrs. thermal exposure. The chemistry of relevant microstructural constituents was analyzed by energy disperse X-ray spectrum (EDS).

Results

Standard Heat Treatment

Table II summarizes mechanical property results for alloys subject to the standard 718 heat treatment. The effect of P and B modification on mechanical properties of alloy 718 can be seen from the results of Group 1 alloys in this table. Consistent with previous studies [1-5], increasing P and B to 0.02% and 0.01%, respectively increased stress rupture life by 60 to 90%. High P and B in conjunction with low C (0.006%) further increased the stress rupture life to 140 to 170% greater than standard 718. The stress rupture life was the lowest when P was reduced to a very low level (0.02%), below the amount present in typical commercial 718. The P and B level had minor effects on tensile properties. Consistent P and B effects were seen in the other alloy groups, but to a lesser extent.

The effect of Al, Ti and Nb modifications on mechanical properties can also be seen from Table II by comparing heats with similar P and B contents from each of the four alloy groups. While the data was somewhat inconsistent, Group 2 (718Ti/Al) and Group 3 (Ticolloy) alloys appeared to have slightly improved stress rupture life compared to standard 718. The degree of improvement due to Al, Ti and Nb changes was smaller than that associated with P and B except for the alloys with the very low P and B content. As was the case with the standard 718 compositions, rupture lives for all of the modified compositions were the lowest, by a significant amount, at the lowest P levels. The data further suggest that the improvement in rupture life due to major strengthening element changes was closely related to the P and B level of the alloys. The greatest relative improvements were seen in alloys with very low P content and decreased with increasing P and B levels. The effect of P and B on rupture lives was smaller in the Al, Ti and Nb modified alloys than in standard 718. It was also apparent that there was no synergistic interaction between P and B and the major strengthening elements and that the latter did not make a significant contribution to improvement in stress rupture properties of 718 with optimum P and B contents.

Table II. Mechanical Properties of Test Alloys Subject to Standard Heat Treatment

Heat No.	Tensile Properties								Stress Rupture			
	20°C				650°C				650°C/ 690 MPa		650°C/ 772 MPa	
	UTS MPa	YS MPa	EL %	RA %	UTS MPa	YS MPa	EL %	RA %	Life Hrs	EL %	Life Hrs	EL %
Group 1: Standard 718 (0.5% Al + 1.0% Ti)												
WD83	1500	1195	25.0	39.2	1180	1005	36.5	73.2	37.6	29.5	16.0	28.5
WE87	1481	1203	22.9	41.0	1214	1045	28.6	66.7	179.3	29.3	52.3	26.6
WD84	1476	1180	24.5	40.1	1203	996	34.5	71.8	290.5	22.0	99.1	22.0
WE91	1482	1199	22.9	43.3	1182	992	34.0	62.9	484.0	18.2	142.2	24.7
Group 2: 718Ti/Al (0.65% Al + 1.35% Ti)												
WD86	1524	1214	24.5	37.4	1180	986	27.5	41.2	70.3	35.5	24.7	29.0
WE89	1513	1199	27.1	39.9	1269	1065	27.4	65.7	241.4	28.4	79.4	30.0
WD85	1500	1187	24.0	37.7	1223	1003	37.5	64.3	375.6	23.0	81.3	21.5
Group 3: Ticolloy (1.0% Al + 1.0% Ti)												
WD91	1504	1150	24.0	40.6	1193	1005	32.5	49.0	81.1	29.0	33.5	26.4
WE88	1513	1178	22.9	38.3	1218	1006	33.2	54.2	189.9	33.1	83.9	34.8
WD88	1516	1196	23.5	36.2	1233	1022	36.0	67.7	226.5	26.0	111.6	28.0
Group 4: 718CM (1.1% Al + 1.25% Ti)												
WD90	1515	1129	23.0	22.2	1213	946	37.0	67.8	52.1	35.5	24.4	34.5
WG45	1508	1174	24.9	39.0	1211	985	22.3	19.5	124.8	23.2	61.1	27.0
WD89	1526	1149	21.5	28.3	1247	963	34.5	61.9	199.1	25.0	110.9	32.6

Note: Standard 718 heat treatment applied to all samples:
954°C x 1 hr., AC, 718°C x 8 hrs., FC at 55°C/hr. to 621°C x 8 hrs., AC

Modified Heat Treatments

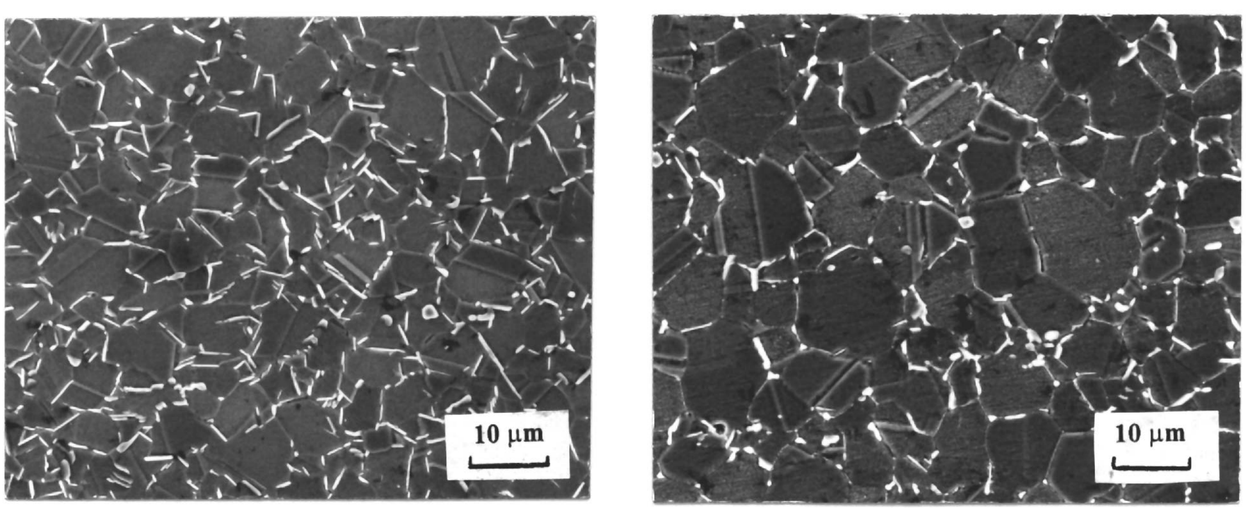
The mechanical properties of test alloys subjected to modified heat treatments are listed in Tables III to VI. Several observations were made from these data:

1. Increasing P and B improved the stress rupture properties of all of the alloy groups except 718Ti/Al without adversely affecting tensile properties. The degree of improvement appeared to be temperature-dependent and diminished with increasing test temperature. Relative improvements in stress rupture life were smallest at 704°C, although all rupture times were very short because of the chosen test conditions. These results nevertheless agreed with earlier work [14], suggesting the strengthening effect of P and B modification diminished significantly at 704°C or higher. The same observation appeared to be true for the modified alloys studied in this work.
2. Al, Ti and Nb chemistry modifications in the modified heat treat conditions appeared to have slightly reduced rupture lives compared to standard 718 and also seemed to influence the strengthening effect of P and B modification. The greatest, relative improvement in stress rupture life at 677°C/690 MPa due to increased P and B was observed in 718CM. Tensile strength of 718CM alloys in the modified heat treat condition, however, was substantially below that of the other three alloys.
3. Strengthening element modifications had a noticeable effect on thermal stability of alloy 718, as measured by the ratio of stress rupture life after 704°C x 1000 hrs. thermal exposure to that in the as heat treated condition (retention ratio R_T). As shown in Tables III to VI, this ratio was about 0.10–0.20 in alloy 718, but increased to about 0.40-0.50 in 718CM which showed the highest stability. The retention ratio was also improved in other modified alloys, but to a lesser degree.

Table III. Effect of 704°C/1000 hr Thermal Exposure on Mechanical Properties of Standard 718 with Different P + B Contents

	Tensile Properties								Stress Rupture			
	20°C				650°C				677°C/ 690 MPa		704°C/ 621 MPa	
	UTS MPa	YS MPa	EL %	RA %	UTS MPa	YS MPa	EL %	RA %	Life Hrs	EL %	Life Hrs	EL %
WE87 (0.008% P + 0.006% B)												
As-Heat Treated	1494	1249	24.1	43.6	1187	1031	29.3	40.6	30.5	41.6	13.1	43.1
704°C/ 1000 hrs	1367	1031	29.3	40.6	1035	878	33.9	73.5	4.1	40.3	2.3	39.0
R_T	0.91	0.83	1.22	0.93	0.87	0.85	1.16	1.81	0.13	0.97	0.16	0.90
WD84 (0.020% P + 0.010% B)												
As-Heat Treated	1475	1206	23.7	39.2	1180	997	35.7	65.2	47.9	29.9	16.9	44.1
704°C/ 1000 hrs	1351	1012	17.9	22.4	1051	845	40.2	75.5	5.7	36.1	2.5	37.7
R_T	0.92	0.84	0.76	0.57	0.89	0.85	1.13	1.16	0.12	1.21	0.15	0.86
WE91 (0.006% C + 0.020% P + 0.010% B)												
As-Heat Treated	1493	1229	23.7	39.7	1187	1012	28.6	56.0	56.0	26.8	17.4	41.1
704°C/ 1000 hrs	1380	1055	18.5	26.3	1058	884	34.4	73.1	6.3	40.3	3.2	38.2
R_T	0.92	0.86	0.78	0.66	0.89	0.87	1.20	1.30	0.11	1.50	0.18	0.93

Notes: 1. All samples heat treated:
982°C x 1 hr., AC, 718°C x 8 hrs., FC at 55°C/hr to 621°C x 8 hrs., AC
2. Retention ratio R_T of a specific property is the ratio of the value after to the value before 704°C/1000 hr. thermal exposure.



(a) (b)

Figure 1: δ-phase and grain structure in Standard 718 (a) and 718CM (b) subject to modified heat treatment.

Table IV. Effect of 704°C/1000 hr. Thermal Exposure on Mechanical Properties of 718Ti/Al with Different P and B Contents

	Tensile Properties								Stress Rupture			
	20°C				650°C				677°C/ 690 MPa		704°C/ 621 MPa	
	UTS MPa	YS MPa	EL %	RA %	UTS MPa	YS MPa	EL %	RA %	Life Hrs	EL %	Life Hrs	EL %
WE89 (0.009% P + 0.005% B)												
As-Heat Treated	1529	1247	20.2	31.4	1231	1048	29.3	66.4	33.6	27.6	13.0	42.1
704°C/ 1000 hrs	1467	1151	11.4	14.1	1140	920	31.0	69.3	8.0	35.8	4.5	57.7
R_T	0.96	0.92	0.56	0.45	0.93	0.88	1.06	1.04	0.24	1.30	0.35	1.37
WD85 (0.021% P + 0.010% B)												
As-Heat Treated	1511	1245	21.9	40.1	1256	1069	30.3	65.3	31.6	37.7	12.7	38.8
704°C/ 1000 hrs	1453	1145	12.2	14.0	1151	954	37.5	71.1	8.4	38.6	5.2	41.0
R_T	0.96	0.92	0.56	0.35	0.92	0.89	1.24	1.09	0.27	1.02	0.41	1.03

Notes: 1. All samples heat treated:
982°C x 1 hr., AC, 760°C x 8 hrs., FC at 55°C/hr to 650°C x 8 hrs., AC
2. Retention ratio R_T of a specific property is the ratio of the value after to the value before 704°C/1000 hr. thermal exposure.

Table V. Effect of 704°C/1000 hr Thermal Exposure on Mechanical Properties of Ticolloy with Different P and B Contents

	Tensile Properties								Stress Rupture			
	20°C				650°C				677°C/ 690 MPa		704°C/ 621 MPa	
	UTS MPa	YS MPa	EL %	RA %	UTS MPa	YS MPa	EL %	RA %	Life Hrs	EL %	Life Hrs	EL %
WE88 (0.008% P + 0.005% B)												
As-Heat Treated	1526	1227	22.9	38.2	1244	1037	27.1	48.7	26.1	40.4	11.3	44.5
704°C/ 1000 hrs	1405	1065	9.0	9.6	1134	931	42.5	72.9	5.3	40.4	4.3	41.0
R_T	0.92	0.87	0.39	0.25	0.91	0.90	1.57	1.50	0.20	1.06	0.38	0.98
WD88 (0.021% P + 0.011% B)												
As-Heat Treated	1520	1223	21.1	32.2	1222	1016	35.0	59.6	41.1	38.0	14.4	42.0
704°C/ 1000 hrs	1431	1067	11.4	13.3	1093	864	41.5	73.2	6.8	40.8	4.9	33.8
R_T	0.94	0.87	0.54	0.41	0.89	0.85	1.19	1.23	0.17	1.01	0.34	0.76

Notes: 1. All samples heat treated:
982°C x 1 hr., AC, 760°C x 8 hrs., FC at 55°C/hr to 650°C x 8 hrs., AC
2. Retention ratio R_T of a specific property is the ratio of the value after to the value before 704°C/1000 hr. thermal exposure.

Table VI. Effect of 704°C/1000 hr Thermal Exposure on Mechanical Properties of 718CM with Different P and B Contents

	Tensile Properties								Stress Rupture			
	20°C				650°C				677°C/ 690 MPa		704°C/ 621 MPa	
	UTS MPa	YS MPa	EL %	RA %	UTS MPa	YS MPa	EL %	RA %	Life Hrs	EL %	Life Hrs	EL %
WG45 (0.008% P + 0.005% B)												
As-Heat Treated	1469	1087	23.7	39.7	1194	907	19.3	23.2	23.1	13.7	11.0	19.1
704°C/ 1000 hrs	1412	1023	18.4	24.4	1147	864	29.0	42.2	10.1	35.2	5.6	33.8
R_T	0.96	0.94	0.78	0.61	0.96	0.95	1.50	1.82	0.44	2.57	0.51	1.77
WD89 (0.021% P + 0.010% B)												
As-Heat Treated	1503	1109	20.1	29.7	1173	922	35.0	65.9	64.6	28.4	13.7	37.7
704°C/ 1000 hrs	1443	1020	11.7	14.3	1091	830	37.3	72.1	21.6	29.1	6.8	34.0
R_T	0.96	0.92	0.58	0.48	0.93	0.90	1.07	1.09	0.33	1.01	0.50	0.91

Notes: 1. All samples heat treated:

982°C x 1 hr., AC

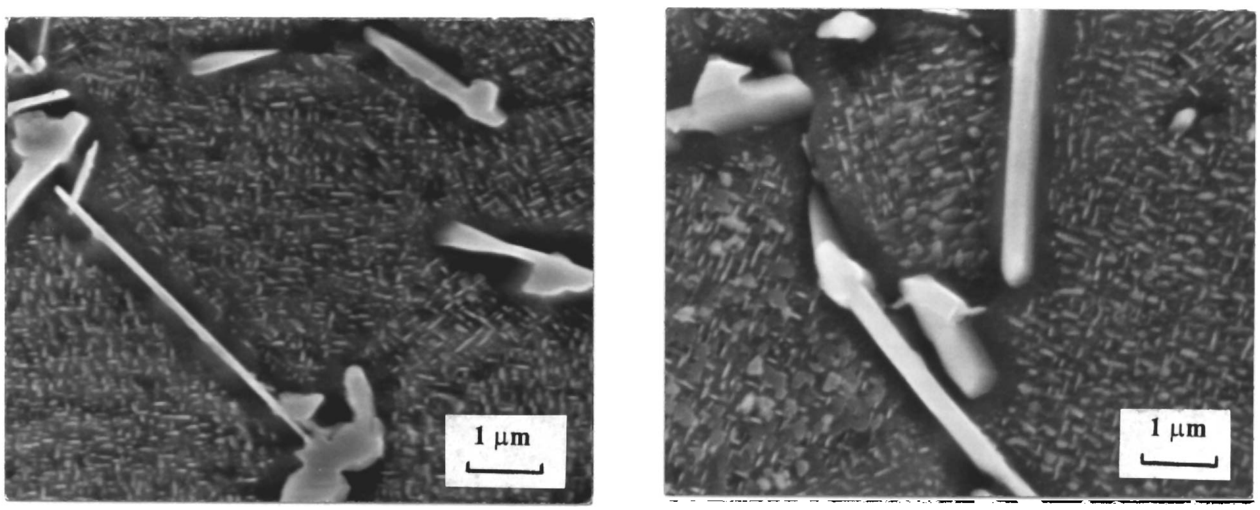
850°C x ½ hrs., FC at 200°C/hr to 650°C x 16 hrs., AC

2. Retention ratio R_T of a specific property is the ratio of the value after to the value before 704°C/1000 hr. thermal exposure.

Microstructures

Chemistry modifications made in this study had no significant effect on grain size. Results varied within a very narrow range and measured about 8–10 μm after the standard heat treatment and 10–12 μm after modified heat treatments. Generally, 718CM had a slightly coarser grain size than the other three groups. The slightly coarser grain size in 718CM may relate to the difference in quantity of δ phase particles. The volume fraction of δ phase particles was slightly reduced in all alloys with modified Al, Ti and Nb contents, but it was noticeably lower in 718CM (Figure 1). The size and morphology of δ phase particles were not changed much by either P and B or Al, Ti and Nb modification.

As reported previously [14], three microstructural changes occurred in alloy 718 during long time heating at 704°C: growth of precipitates γ' and γ'', formation of a γ''-depletion zone at grain boundaries and formation of Nb-containing blocky particles. The same changes occurred in all test alloys in this study, but the degree of changes did vary in different alloys. These differences can be seen from Figures 2 and 3. Figure 2 shows the microstructures of alloy 718 after 704°C x 1000 hrs. thermal exposure. A precipitate depleted zone can be clearly seen around needle-like δ phase particles and newly formed blocky particles. Remaining precipitates barely visible in the depleted zone were predominantly spherical γ' particles, but the density was low. Both γ' and γ'' particles had grown to a size distinguishable at 3000X, and it seemed that P and B had no noticeable effect on the size of these particles. The blocky particles newly formed during heating had an average Nb content lower than that of δ phase, and were probably in the process of transforming to δ phase. In comparison with microstructures of alloy 718 shown in Figures 2 (a) and (b), several differences were noticed in 718CM as illustrated in Figure 3. It can be seen from Figure 3 that the size of precipitate particles was smaller for alloy 718CM, indicating that Al, Ti and Nb modification retarded precipitate growth. The quantity of γ'' particles was reduced and quantity of spherical γ' particles increased. Those observations are consistent with the results reported in many references. The alloys with modified strengthening elements and standard P and B contents actually showed a wider γ'' depleted zone, but a higher density of γ' particles. Increasing P and B significantly reduced the width of γ'' depleted zone in alloy 718CM as clearly seen in Figures 3 (a) and (c) at lower magnification. The same phenomenon existed in other Al and Ti modified alloys of this study, but to a much lesser degree. This may imply that increased P and B might stabilize γ'' particles. No noticeable effect of P and B modification on γ' particles was observed. More work is necessary to fully characterize the changes caused by modifying minor and strengthening elements in alloy 718.

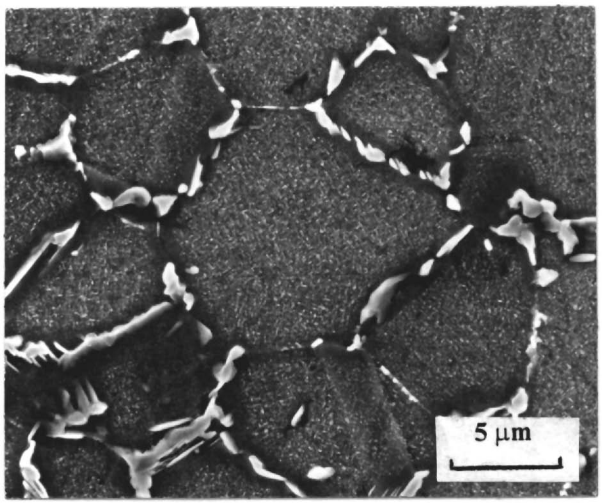


(a) (b)

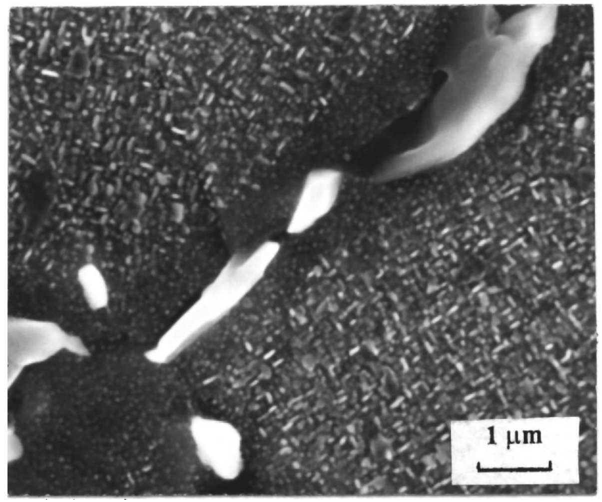
Figure 2: Microstructures of Standard 718 after 704°C x 1000 hrs. thermal exposure (a) 0.008 P, 0.005 B (b) 0.020 P, 0.010 B.

Discussion

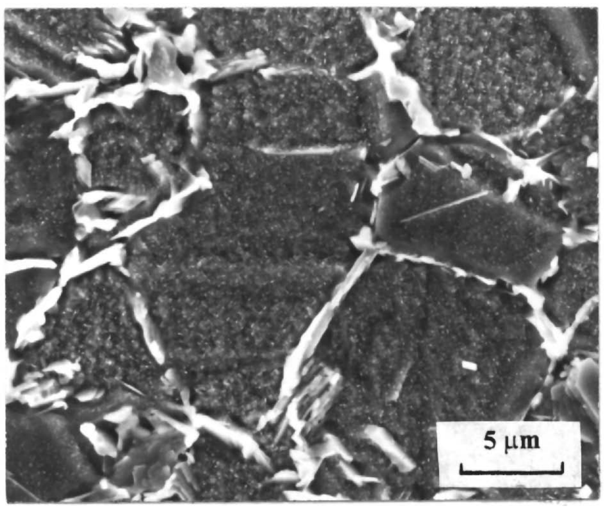
This study shows that increasing P and B improved stress rupture properties of both standard and modified alloy 718, but the improvement diminished with increasing test temperature and especially after long time heating at high temperature. This can be clearly seen in Figure 4 where the ratios of stress rupture life at increased P and B levels to that at standard P and B levels (R_P) are plotted by test alloys. Except for 718Ti/Al, the ratios were all greater than 1.0, showing that stress rupture life improved by increasing P and B, and decreased with increasing test temperature and after 1000 hrs. thermal exposure at 704°C. A similar trend was observed in previous work with standard 718 [14] and was explained in terms of the interaction between P and B atoms and γ'' particles. It was suggested that the strengthening effect of P and B additions might be partially associated with γ'' particles and would be reduced with a loss of the strengthening effect of γ'' and with a reduction in its volume fraction. Thus the reduced effectiveness of γ'' strengthening at higher test temperatures and the formation of γ''-depleted zone after long time heating would lead to a reduction in the strengthening effect from P and B modification. This postulation is supported by this study. The higher R_P ratios observed in 718CM at 677°C/690 MPa can also be explained by this effect. As shown in Figure 3, a smaller γ''- depleted zone formed after thermal exposure in 718CM with increased P and B contents; thus it can be assumed, maintaining more of the strengthening effect of P and B modification.



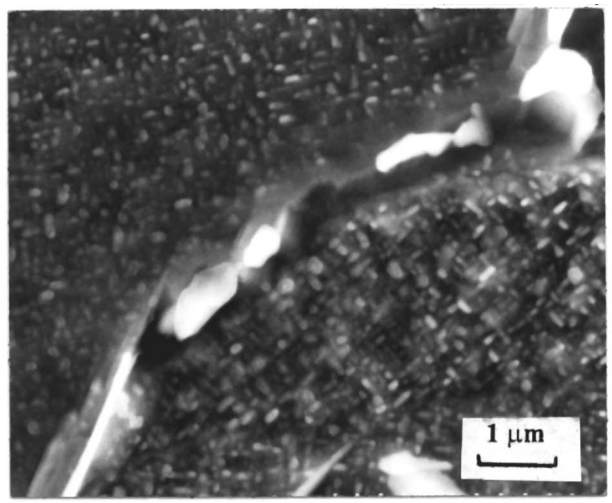
(a)



(b)

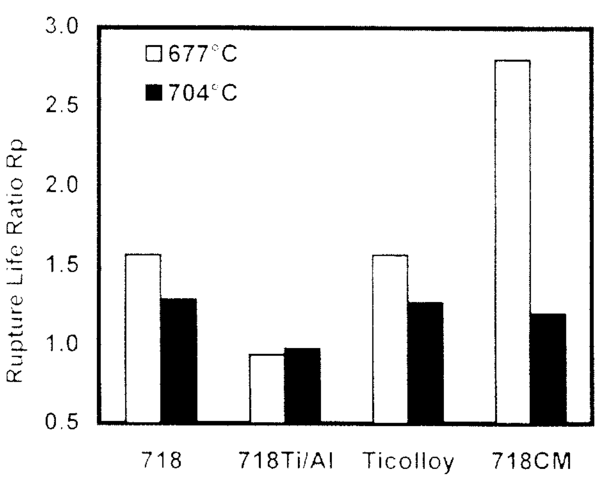


(c)

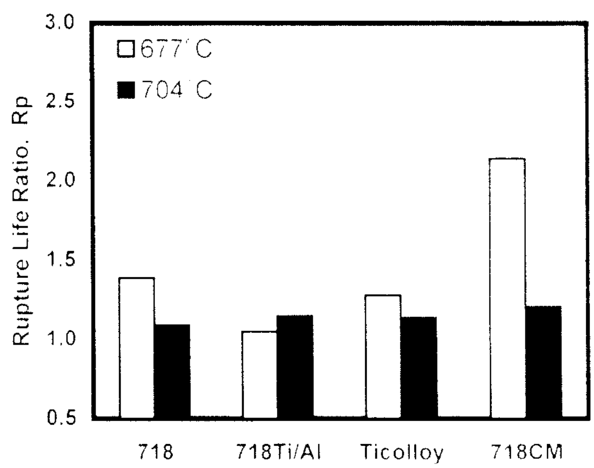


(d)

Figure 3: Microstructure of Alloy 718CM after 704°C x 1000 hrs. thermal exposure (a) and (b) at standard P and B levels, (c) and (d) at increased P and B levels.



(a)



(b)

Figure 4: Ratio of stress rupture life at increased P and B levels to that at standard P and B levels (a) as-heated and (b) after 704°C x 1000 hrs. thermal exposure.

The increase in stress rupture life by Al, Ti and Nb modifications in the standard heat treatment condition (Table II) was most likely due to γ' particles, since all of the modifications used have an increased volume fraction of γ'.

The reduction in stress rupture life for the Al, Ti and Nb modified alloys in the modified heat treat condition was most likely caused by a change in the size and relative quantity of γ' and γ'' particles; since the purpose of the modified aging treatments was to obtain more stable precipitates to maximize properties at higher temperatures. This was especially true for 718CM where a stable, compact morphology of γ'/γ'' particles forms from the high aging temperatures. This heat treatment caused the growth of precipitates and the reduction in γ'' particles, resulting in lower strength and rupture life as heat treated. Thermal stability, however, was increased due to this special morphology and increased quantity of γ' particles, as shown by the higher retention ratio for both tensile strength and stress rupture life (Tables III and VI).

The increase in thermal stability achieved by strengthening element modification created the possibility of maintaining the improvement in stress rupture properties due to P and B modification to higher temperatures. Alloy modification in 718CM with high P and B contents produced the best results in this regard. No attempt was made to quantitatively evaluate the improvement in temperature capability of such modifications, but it was moderate and probably not greater than 25°C. However, further improvements may be possible.

Conclusions

1. Al, Ti and Nb modifications suggested in the literature moderately improved the stress rupture life of alloy 718 in the standard heat treatment condition. Modified heat treatment conditions recommended to give a more stable precipitation morphology lowered the rupture life.
2. Al, Ti and Nb modifications appeared to increase the thermal stability of alloy 718, as shown by higher stress rupture life after 704°C x 1000 hrs. thermal exposure. Extremely short lives and small differences in the absolute numbers suggest additional testing on the issue of thermal stability is necessary.
3. Increased P and B levels significantly improved stress rupture life of standard and modified alloy 718. The improvement diminished with increasing test temperature and after long time heating at high temperature. The retention ratio of stress rupture life was basically the same for standard and P and B modified alloys, indicating that P and B modification did not improve thermal stability.
4. Combining Al, Ti and Nb and P and B modifications further improved the stress rupture life of alloy 718 and more importantly maintained the improvement from P and B modification to higher temperature. The best results were achieved from alloy 718CM with increased P and B levels.

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