Superalloys 2004
Edited by K.A. Green, T.M. Pollock, H. Harada,
T.E. Howson, R.C. Reed, J.J. Schirra, and S, Walston
TMS (The Minerals, Metals & Materials Society), 2004

ROLE OF CHEMISTRY IN 718-TYPE ALLOYS – ALLVAC® 718PLUS™ ALLOY DEVELOPMENT

Wei-Di Cao and Richard Kennedy
ATI Allvac, 2020 Ashcraft Avenue, Monroe, NC 28110, USA

Keywords: 718, 718Plus, Chemistry, Mechanical Properties, Thermal Stability, Waspaloy

Abstract

The role of important alloying elements in 718-type alloys (Ni-Cr-Fe base alloys with Nb as one of the major hardening elements) was investigated by modeling and experiments. It was found that modifying the Al/Ti ratio and increasing Al+Ti content converted the alloy into a predominantly γ' strengthening alloy having improved thermal stability. Optimum mechanical properties were obtained with an Al/Ti (at%) ratio of 4 and an Al+Ti level at 4 at%. Adding Co up to about 9 wt% also improved the mechanical properties and thermal stability. Still further improvement occurred with Fe content of 10 wt%, 2.8 wt% Mo and 1 wt% W. Very small additions of P and B further increased stress rupture and creep resistance. A new alloy, Allvac® 718Plus™[i], was developed from this work exhibiting a 55°C (100°F) higher temperature capability, while maintaining the excellent processability of Alloy 718.

Introduction

Nickel-iron base superalloys with niobium as one of the major precipitation hardening elements, exemplified by Alloy 718, have become the most widely used superalloys. The extensive application of 718 stems from its excellent mechanical properties, good processing characteristics, such as hot workability and weldability, and relatively low cost.

For many years, there has been interest in an affordable 718-type alloy that would have a temperature capability higher than Alloy 718. This interest is driven by the fact that the upper use temperature for 718 is limited to 650°C. Alloy 718 is predominantly strengthened by coherent γ" phase that is thermodynamically unstable at high temperatures. The γ" phase transforms to incoherent δ phase and the mechanical properties deteriorate rapidly. For long-term applications at temperatures above 650°C, other, more expensive and difficult-to-process alloys such as Waspaloy, Rene' 41 and U-720 have to be used. These limitations define the opportunity for a new, improved 718-type superalloy. The desirable features of such an alloy would include:

- An increase in manufacturing use temperature over 718 with comparable mechanical properties and good thermal stability to 704°C.
- Processing characteristics similar to Alloy 718 and better than those of the γ' hardened alloys required for higher temperature applications.
- Raw material and manufacturing costs lower than those of the γ' hardened alloys.

There have been many attempts to improve on the temperature capability of 718. Most of the work has been directed at increasing the strengthening effect and thermal stability of the γ" phase, in a predominantly γ"- strengthening alloy. Another approach was to develop an improved γ' phase strengthened alloy having better processing characteristics, better mechanical properties and lower cost. A third approach examined the addition of trace elements. Examples include 718 with increasing Al and Ti levels and modified Al/Ti ratios (Ticolloy) [1, 2, 3, 4], 718 with Al+Ti/Nb ratio changes to permit development of a compact morphology of γ'/γ" [5, 6, 7] and alloys with reduced iron and additions of Ta and Co such as Rene' 220 [8, 9] and GE alloy 991 [10]. The effect of trace elements P and B were studied by the authors [11, 12, 13]. However, none of the newly developed alloys successfully met all of the desired requirements outlined above.

It was felt that a systematic and broader study was needed to fully understand the effects of key alloying elements on microstructure, mechanical properties, thermal stability and processing characteristics of 718-type alloys. A research program was launched in 1997 in which the roles of precipitation hardening elements Al, Ti and Nb, matrix elements Fe, Co, Mo and W, and minor elements P and B were examined. The contents of elements in the study were varied over much wider ranges than those observed in normal 718-type alloys. Thermo-Calc and JMatPro modeling software programs were employed to predict stable phase and precipitation kinetic behavior of various compositions. More than 100 pilot plant heats weighing from 23-136 kg were made by VIM/VAR and used to experimentally evaluate the effects of various elements on microstructure, mechanical properties and performance in processing. As a result of this program, a new alloy, 718Plus, was developed that meets all of the desirable features for a 718 + 55°C (100°F) alloy.

Alloy Design Approach

There were several important components of the alloy design approach, which were felt to be critical to achieving overall program goals:

Precipitation Modification

Thermal stability is a key requirement to achieving a 55°C (100°F) increase in maximum use temperature. Gamma prime phase strengthened alloys have inherently higher thermal stability than γ" phase alloys. While stability of the latter might be improved by chemistry modifications, there is no data showing that the thermal stability of a γ" phase strengthening alloy can be raised to the same level as that of a γ' phase strengthening alloy. This suggested the need for a predominately γ' hardened alloy.

It is well established that the rapid precipitation kinetics in conventional γ' phase strengthening alloys is responsible for their relatively poor performance in hot working and welding. The γ'

[i] Allvac® 718Plus™ is a trademark of ATI Properties, Inc.

phase in a new alloy would preferably have much slower precipitation kinetics than Waspaloy.

While a low γ-γ' lattice mismatch minimizes the γ' coarsening rate and increases creep stability, it also leads to low strength. To achieve sufficient strength, a higher volume fraction of γ' is needed, but the amount permitted will be restricted by processing.

The $L1_2$ (γ') structure can transform to DO_{19} (η) and DO_{22} (δ) structures, leading to degradation of properties. Stability of γ' phase could be significantly changed by adding Ta, Nb, Ti, and to a lesser degree, W and Mo which may also change the properties and precipitation kinetics of γ' [14, 15, 16]. The high price of Ta excludes it from this study. Therefore, Nb and Ti become the elements of choice for an affordable alloy design.

Matrix Optimization

Mechanical properties and processing characteristics of superalloys are determined not only by precipitation hardening phases but also by the alloy matrix. The matrix can be strengthened by solid solution hardening and also by increasing the efficiency of precipitation hardening. Elements Co, Mo and Cr reduce stacking fault energy of the γ matrix and also change the volume of precipitated phases. W partitions mainly to the γ matrix to strengthen it by solid solution hardening and reducing bulk diffusivity. Some newly developed 718-type alloys tend to exclude Fe from their chemistry. However, this is not desirable from a cost standpoint. It is critical to understand the role of matrix elements.

Minor Elements

Previous studies [12, 13] demonstrated that minor elements P and B are effective in increasing the stress rupture/creep strength in Alloy 718 in a very cost-effective way. It is worthwhile to see if P and B have a similar effect in a new alloy, and to determine their influence on the processing characteristics.

Results and Discussion

Al, Ti and Nb

Modeling. Modeling calculations were performed on selected alloys using the JMatPro 2.0 program [17] whenever possible to address the issues addressed in the Alloy Design section. The calculations were done first on a 718-base alloy and then on alloys with Co and Fe modifications to determine the effect of matrix elements. Tungsten, P and B were not included because they are not in the current database. The effect of Al and Ti were examined at constant Nb level, and then the level of Nb was changed to determine its effect. Calculations were performed on model alloys located at each of the Al+Ti and Al/Ti line intersections shown in Fig. 1. Higher Al+Ti levels were not included because of the processability considerations.

Fig. 2 shows the predicted stable phases at 650°C in Alloy 718 as a function of Al and Ti contents. Results for alloys with a modified 718 base composition containing 9%Co[ii] and 10%Fe are also included. As described later, these are the preferable Co and Fe contents in Alloy 718Plus. The model predicts few differences for these two base alloy systems, indicating that the matrix chemistry has little effect on the phase diagrams. Calculations were also performed with all TCP phases and all TCP + δ and η phases suspended to show the compositional dependence of the amounts of γ' and γ''. Results for alloys with modified Co and Fe levels are listed in Tables I and II.

Table I. Predicted Phase Content at 650°C with Differing Al/Ti Ratios (Modified 718 Base Alloy, Al+Ti = 4 at%, Phase Content Expressed in Mole %)

Phase	**Al/Ti (at%) Ratio**							
	∞	**8**	**4**	**2**	**1**	**0.5**	**0.25**	**0**
TCP Phases Suspended								
γ'	20.90	20.39	20.06	19.55	18.87	8.97	0.44	0
δ	7.59	8.18	8.65	9.40	10.48	9.99	10.03	10.88
η	0	0	0	0	0	10.65	18.50	18.98
TCP, δ and η Phases Suspended								
γ'	24.66	23.88	23.32	22.50	21.56	20.84	18.50	14.91
γ''	4.39	5.14	5.74	6.67	7.87	9.25	11.23	14.90

Table II. Predicted Phase Content at 650°C with Differing Al+Ti Levels (Modified 718 Base Alloy, Al/Ti (at%) = 4, Phase Content Expressed in Mole %)

Phase	**Al+Ti (at%)**				
	0	**1**	**2**	**3**	**4**
TCP Phases Suspended					
γ'	0	0.60	6.85	13.42	20.06
δ	13.80	14.95	12.91	10.84	8.65
η	0	0	0	0	0
TCP, δ and η Phases Suspended					
γ'	0	2.08	9.11	16.23	23.32
γ''	13.44	13.59	11.04	8.42	5.74

Two important results are apparent from these tables. First, the phase stability of γ' is strongly influenced by the Al/Ti ratio as shown by the low levels of γ' phase and large amounts of δ, and especially η phases, at low Al/Ti ratios. Secondly, the quantity of γ' phase increases linearly with increasing Al+Ti content. To achieve a γ'-dominant alloy (γ' more than 80% of total hardening precipitates) the Al+Ti content must be higher than 3 at% even for alloys with a high Al/Ti ratio.

Table III lists the calculated time for the start of precipitation of various phases at the nose temperature of their respective TTT curves in Co and Fe-modified alloys with Al+Ti = 4 at%. These results show that alloys with low Al/Ti ratio have a much faster δ and η phase precipitation rate. However, as Table IV shows, the γ' growth rate decreases with decreasing Al/Ti ratio. The γ' phase precipitation rate is also higher in alloys with a low Al/Ti ratio. At the higher Al/Ti ratios, the strengthening phase precipitation kinetics are higher than Alloy 718, but lower than Waspaloy. Table IV shows the growth rate of γ' decreases with decreasing Al/Ti ratio which should favor improved property stability.

[ii] All compositions represent weight percent unless specifically stated as atomic percent (at%).

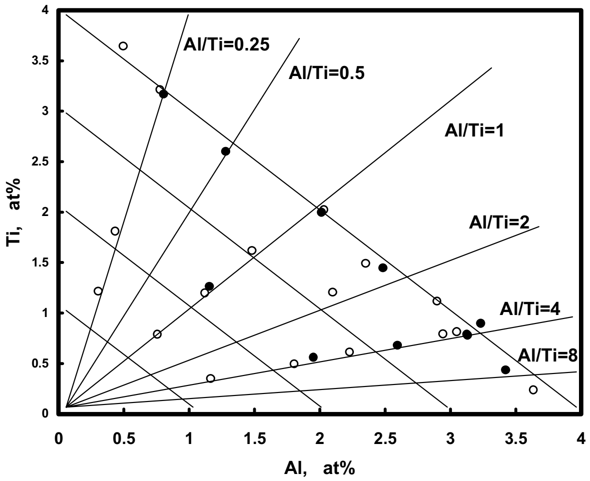


Fig. 1. Al-Ti map of alloys for modeling calculation and experimental study. Open circles indicate the Al and Ti contents for Alloy 718 and solid circles for modified Alloy 718.

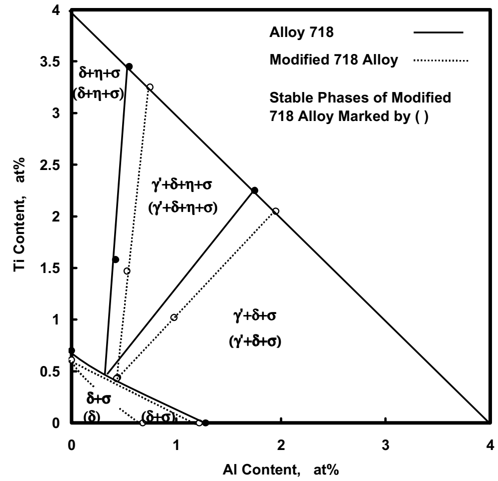


Fig. 2. Stable phases at 650°C as a function of Al and Ti levels of Alloy 718 and Modified Alloy 718.

Table III. Effect of Al/Ti Ratio on Precipitation Kinetics (Modified 718 Base Alloys, Al+Ti = 4 at%)

Precipitation Phase	Time to 0.5 Mole % Precipitation at Nose of TTT Curves, Hrs									
	Alloy 718	Waspaloy	Al/Ti (at%) Ratio							
			∞	8	4	2	1	0.5	0.25	0
γ'	0.100	0.007	0.021	0.013	0.010	0.007	0.005	0.004	0.005	0.010
γ''	0.057	–	0.023	0.020	0.017	0.014	0.010	0.007	0.006	0.005
δ	0.42	–	0.15	0.14	0.12	0.11	0.086	0.066	0.064	0.061
η	4.86	–	–	1.86	0.65	0.22	0.079	0.031	0.032	0.034

Table IV. Effect of Al/Ti Ratio on Growth Rate of γ' Particle in Model Alloy (Modified 718 Alloys with Al+Ti = 4 at%)

	Alloy 718	Waspaloy	Al/Ti (at%) Ratio							
			∞	8	4	2	1	0.5	0.25	0
γ' Growth Rate (nm/hr)$^{1/3}$	4.98	7.00	5.17	5.11	5.05	4.91	4.69	4.45	4.29	4.00

The effect of Al/Ti ratio on the strengthening effect of γ' phase was evaluated from calculations of γ-γ' mismatch. The strengthening effect of γ' phase does not solely come from coherency strain hardening, but it is a good indication. Table V shows the γ-γ' mismatch of the modified alloys compared with Waspaloy. The larger mismatch in 718-type alloys is most likely due to the Nb partitioning to γ'. While decreasing Al/Ti ratios favor increased mismatch and thereby strength, the negative effect would be lower stability and more δ and η phases, as shown in Table I.

The effects of 4.5 – 6.5%Nb were modeled in alloys with 18%Cr-10%Fe-9%Co-1.5%Al-0.7%Ti, which appeared to be the most favorable chemistry for Alloy 718Plus. Results suggested higher Nb increases the volume fraction of γ' and γ'' phases and expands the regions of η and σ but does not significantly affect γ' particle coarsening rate or γ-γ' mismatch within the limited range studied. Increased Nb also favors γ'', shifting the stable γ' range to higher Al and Ti levels. These results imply that Nb is desirable from a property standpoint, but its content must be carefully balanced with Al+Ti to achieve alloy design goals.

Table V. Effect of Al /Ti Ratio on γ- γ' Mismatch in Model Alloy (Modified 718 Alloys with Al+Ti = 4 at%)

	Mismatch, x 10^{-3}								
	Alloy 718	Waspaloy	Al/Ti (at%) Ratio						
			∞	8	4	2	1	0.5	0.25
25°C	6.54	4.17	6.18	6.18	6.43	6.88	7.47	7.55	7.58
704°C	5.11	2.44	4.39	4.70	4.97	5.36	5.91	5.94	–
760°C	4.66	2.29	3.83	4.14	4.41	4.85	5.32	5.32	–

Experimental Results. Modeling calculations provide important information on the effects of chemistry changes but cannot accurately predict the preferred final chemistry. Experimental studies are still necessary to determine an optimum chemistry.

Test alloys were made by vacuum induction melting plus vacuum arc remelting techniques (VIM/VAR) as 23-136 kg heats. After homogenization, ingots were press-forged to 50 mm square billets and further rolled into 19 mm bars. Sample blanks were cut from rolled bars and subjected to the standard heat treatment for Alloy 718 (954°C x 1 hr, air cool, plus 718°C x 8 hrs, furnace cool at 55°C/hr to 621°C x 8 hrs and air cool). Tensile tests were performed at room temperature, 650°C and 704°C, and stress rupture tests at 704°C / 552 or 621 MPa. All test results reported were the average of at least two independent tests. Thermal stability was evaluated by exposing as-heat treated samples to 704°C for 1000 hrs or 760°C for 100 hrs and then testing as above. The ratio of heat-treated + thermally exposed to as-heat-treated properties, designated as retention rate "R," was calculated as a measure of thermal stability. A high R-value, approaching 1, means high thermal stability. Discussion and graphical presentation of results have been restricted mainly to stress rupture properties due to space limitations and because the effect on tensile properties was not as large.

The effect of Al and Ti on mechanical properties was examined in a 718 base alloy (Ni-18%Cr-17.5%Fe-2.9%Mo-5.4%Nb) with Al+Ti = 4 at%. Results showed that that the as-heat treated yield strength decreased with increasing Al/Ti ratio, but the thermal stability was much higher with a high Al/Ti ratio. An optimum combination of yield strength before and after thermal exposure resulted from an Al/Ti (at%) ratio of about 4. The highest stress rupture life of both before and after thermal exposure also occurred at an Al/Ti (at%) ratio of 4 as shown in Fig. 3. Very similar behavior was observed in the modified 718 base alloy (Ni-18%Cr-10%Fe-9%Mo-2.8%Mo-1%W-5.5%Nb). Fig. 4 shows the optimum rupture life and retention rate resulted from an Al/Ti (at%) ratio of about 4. The effect of Al+Ti content on rupture life in the modified alloy was different at different Al/Ti ratios (Fig. 5). With the lower Al/Ti (at%) ratio of 1, typical of the level in Alloy 718, increasing Al+Ti content actually decreased rupture life. However, at the high Al/Ti (at%) ratio of 4, rupture life increased continuously with increasing Al+Ti content.

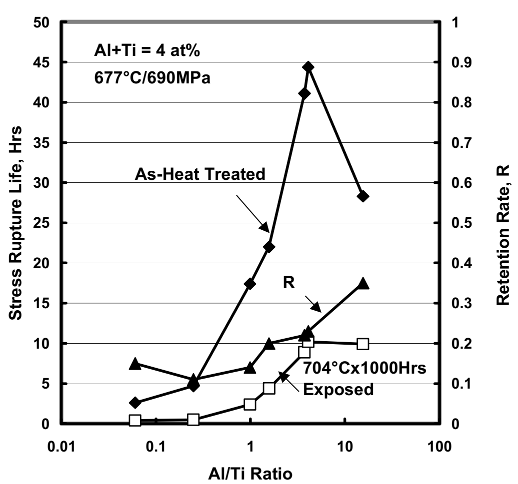


Fig. 3. Effect of Al/Ti ratio on stress rupture life in Alloy 718 base.

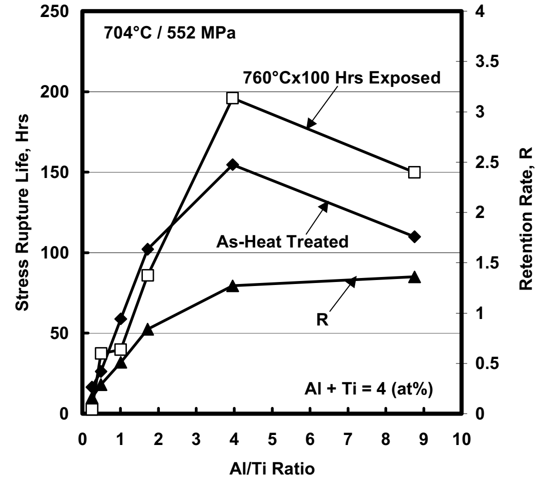


Fig. 4. Stress rupture life as a function of Al/Ti Ratio in modified Alloy 718.

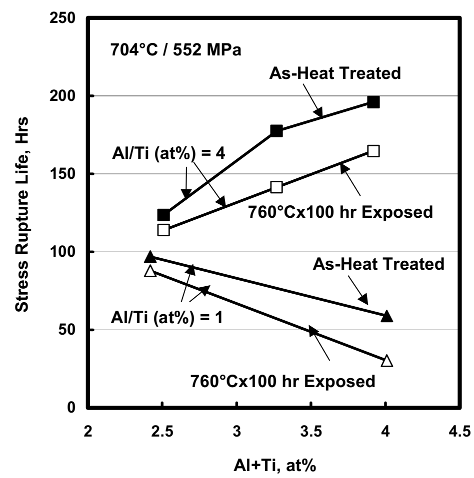


Fig. 5. Stress rupture life as a function of Al+Ti level and Al/Ti ratio in modified Alloy 718.

Combining the results of modeling and experimental work suggests that the major influence of Al and Ti on mechanical properties comes from the stability of the γ' and γ". Lower properties, both as heat treat and after thermal exposure, correlates with the increased tendency for δ and η formation and the rapid overaging and transformation of γ' and γ" to δ and η phases. Microstructural evidence of this is shown in Fig. 6. Following 1000 hours exposure at 704°C, the microstructure of an alloy with a higher Al/Ti ratio still shows a relatively fine, spherical matrix precipitate. The low Al/Ti ratio alloy in contrast showed a larger, disk shaped precipitate and much more of the large needle shaped grain boundary particles, probably δ and η phases. Thus, for a 718 + 55°C (100°F)-type alloy, a high Al+Ti level and high Al/Ti ratio is preferred. This is very different from current 718-type alloys which normally have low Al and Ti contents and a low Al/Ti ratio. The optimum content appears to be about Al+Ti = 4 at% and Al/Ti (at%) = 4. The upper limit of Al+Ti is restricted largely by processibility considerations and the optimum Al/Ti ratio by mechanical properties and stability after thermal exposure.

(a) Al/Ti = 3.8

(b) Al/Ti = 1.5

Fig. 6. Microstructure of Alloy 718 after 704°C x 1000 hrs thermal exposure.

The effect of Nb was studied in test alloys with a base composition of Ni-18%Cr-10%Fe-9%Co-2.9%Mo (Fig. 7). Increasing Nb from 4.5 to 6.5% increased stress rupture life for alloys with a high Al/Ti ratio, but only up to about 5.5%. Higher levels of Nb decreased both life and ductility and heavy forging cracking occurred in alloys with Nb of 6.5%. Similar to the results of increases in Al+Ti content, increasing Nb content did not improve rupture life for low Al/Ti ratio alloys.

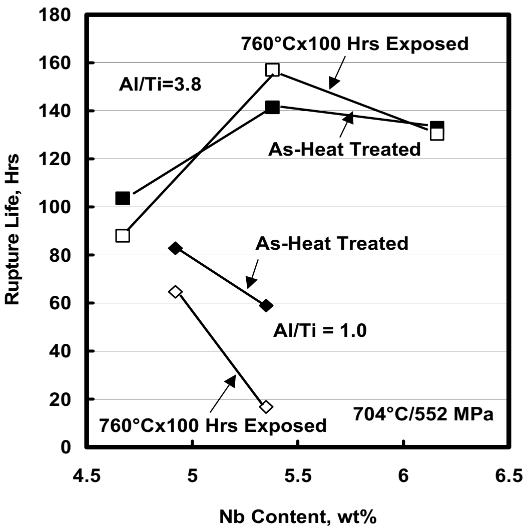


Fig. 7. Effect of Nb content on stress rupture life of modified 718 base alloys.

Fe and Co

Modeling: The effect of Co and Fe on microstructure and mechanical properties was examined in modified 718 alloys with Ni-18%Cr-2.8%Mo-1.5%Al-0.7%Ti-5.5%Nb, the optimum levels as discussed above.

Modeling calculations were performed on a series of compositions with Fe contents of 0, 6, 10, 14 and 18% and Co contents of 0, 3, 5 9, 12 and 15%. Results suggested the effects of Co and Fe in this type of alloy are similar except for their effect on the precipitate/matrix mismatch. The results can be briefly summarized as follows:

- Both elements slightly increased the volume fraction of γ' phase. The increase was minor, less than a half percent within the ranges studied.
- Increasing Fe and Co levels significantly increased the equilibrium content of TCP phases such as σ phase. Fe also promoted the formation of Laves phase.
- Both Fe and Co accelerated the precipitation of all phases involved in the calculation (γ', γ'', δ and η phases).
- Increasing Co level enhanced γ-γ' mismatch. The effect is especially strong at lower Co levels and saturated around 9%. Fe addition decreased the γ'-γ' mismatch.

Thus the addition of Co and reduction in Fe content from standard Alloy 718 levels, could be beneficial by increasing mismatch and volume fraction of γ'. The amount of Co added should not be too high due to the tendency for increased amounts and precipitation rates for TCP phases.

Experimental Results. A number of test alloys with a 718Plus base composition of 18%Cr-2.8%Mo-10Fe-5.5%Nb-1.5%Al-0.7%Ti were prepared by the same methods previously described. Co did not show a strong effect on tensile properties although thermal stability was improved. The retention rate, R reached 1.0 or higher at Co levels of 9%. Co additions did produce a very significant improvement on stress rupture life as shown in Fig. 8. The greatest increase occurred at low Co levels. Peak rupture life in combination with the best thermal stability resulted at 9%Co. Cobalt levels greater than about 9% are not required from a property standpoint and would certainly not be desirable from a cost standpoint.

The effect of Fe was studied in a base composition of Ni-18%Cr-2.8%Mo-5.5%Nb-1.5%Al-0.7%Ti at three Co levels, 0%, 5% and 9%. The effect of Fe on 650°C yield strength in the as-heat treated condition was relatively insignificant, but the stability decreased significantly at the highest Fe levels of 14 and 18%. Fe content strongly influenced stress rupture properties, as shown in Fig. 9, for the 9%Co alloy. Rupture life, both before and after thermal exposure, peaked at the 10% Fe level. Similar behavior was shown for 5%Co level alloys. These results were not consistent with expectations based on modeling predictions. Frequent notch breaks were also observed at 0 to 18%Fe levels. In summary, these results suggest the most preferable Fe and Co levels, for this type of alloy, would be about 10%Fe and 9%Co from the standpoints of both properties and cost.

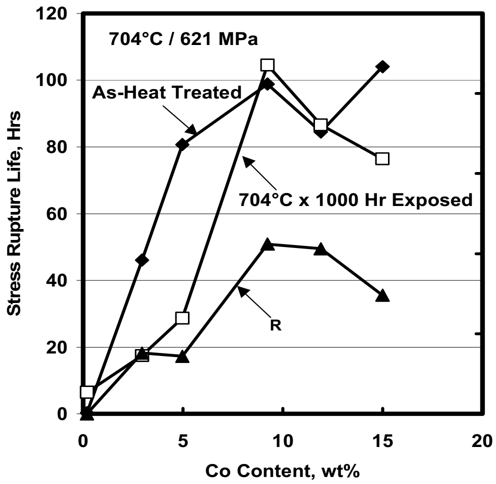


Fig. 8. Effect of Co content on stress rupture life of 718Plus base alloys.

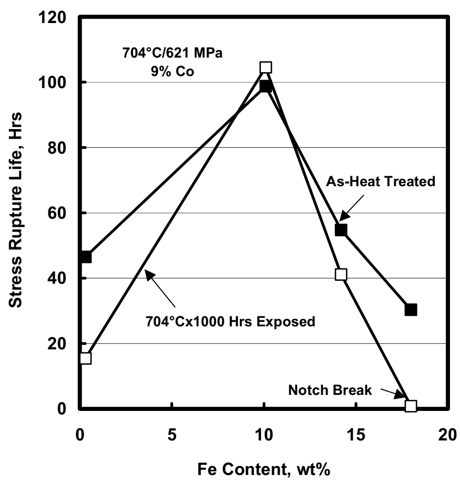


Fig. 9. Effect of Fe content on stress rupture life of modified 718 base alloys.

W and Mo

Additions of W up to 6% were tested in a base composition of Ni-18%Cr-10%Fe-9%Co-5.5%Nb-1.5%Al-0.75%Ti with Mo at 0 and 2.9% levels.

Six alloys were made and tested in the same manner described above. Elevated temperature tensile results were not significantly effected by W additions at either Mo level, although tensile property stability was better with Mo and W additions. The results of stress rupture testing are presented in Table VI.

Table VI. Effect of W & Mo Contents on Stress Rupture Properties @ 704°C/552 MPa (718Plus Base Composition)

Mo%	W%	Rupture Life Hrs)	%EL
0	0	29.3	One N.B.
0	4	0.4	Two N.B.
0	6	141.2	One N.B.
2.9	0	113.1	46.1
2.9	1	154.7	23.3
2.9	2.3	138.3	One N.B.

Alloys without Mo experienced a large number of notch breaks. Adding a small amount of W (1%) to an alloy with the standard 718 Mo level (2.9%) gave improved stress rupture properties.

P and B

The effect of minor elements P and B was experimentally examined, in the same manner described above, on a series of alloys with a 718Plus composition of Ni-18%Cr-10%Fe-9%Co-2.8%Mo-1%W-5.5% Nb-1.5%Al-0.7%Ti.

The stress rupture lives of alloys with different P and B additions are shown in Fig. 10. All test alloys have the same base composition of 18%Cr-10%Fe-9%Co-2.8%Mo-1%W-5.5%Nb-1.5% Al-0.7%Ti (718Plus). The results are consistent with previous studies on Alloy 718 [12, 13] which showed that increasing P and B levels improved stress rupture life significantly. Optimum results appear to occur at lower levels in this work (about 0.013-0.017P, 0.004-0.008B), which may be fortunate since it has been shown [18, 19] that P and especially B are detrimental to weldability of Alloy 718. However, fillerless fusion welding tests have shown no weld cracking with up to 0.02%P and 0.008%B additions in this alloy. Small amounts of P and B additions can be considered as a cost-effective option to improve stress rupture and creep life.

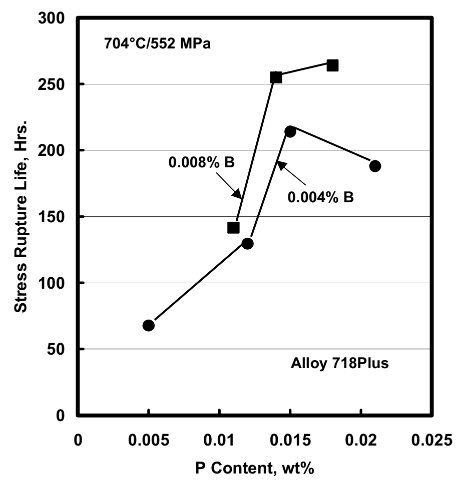


Fig. 10. Effect of P and B Levels on Stress Rupture Life of Alloy 718Plus.

Alloy 718Plus Development

A new alloy, 718Plus, was developed on the basis of knowledge gained from this study. The nominal chemistry is presented in Table VII. Extensive testing has been conducted at both pilot plant and full production scale, and the results have demonstrated a 55°C (100°F) higher temperature capability than Alloy 718, as shown in Fig. 11. Elevated temperature mechanical properties of this alloy are listed in Table VIII, and it can be seen that mechanical properties and thermal stability after long time thermal exposure are much better than Alloy 718 and equal to or better than Waspaloy up to 704°C. The improved thermal stability of this alloy is also apparent from the microstructures shown in Fig. 12. After 350 hrs exposure at 760°C, Alloy 718 contains large overaged γ'' and large, transformed δ phase particles. In comparison, much less δ phase (none shown) is present along

Table VII. Chemistry of Allvac® 718Plus™ in Comparison with Alloy 718 and Waspaloy

Alloy	Chemistry											
	C	Ni	Cr	Mo	W	Co	Fe	Nb	Ti	Al	P	B
Allvac 718Plus	0.020	–	18.00	2.80	1.0	9.0	10.00	5.45	0.70	1.45	0.007	0.004
Alloy 718	0.025	–	18.10	2.90	–	–	18.00	5.40	1.00	0.45	0.007	0.004
Waspaloy	0.035	–	19.40	4.25	–	13.25	—	–	3.00	1.30	0.006	0.006

Table VIII. Mechanical Properties and Thermal Stability of Allvac® 718Plus™
in Comparison with Alloy 718 and Waspaloy

			Tensile at 1300°F				Stress Rupture 704°C/552 MPa		Creep 704°C/483 MPa	
Alloy	**G.S. ASTM**	**Heat Treatment**	**UTS MPa**	**YS MPa**	**EL %**	**RA %**	**Life, Hrs**	**EL, %**	**$t_{0.2}$ Hrs**	**$t_{0.5}$ Hrs**
718	6	As-HT [1]	1015	936	20.3	27.5	157.9	19.5	29.0	63.5
		+ 760°C/350 Hrs	762	543	53.8	62.3	13.7	34.2	–	–
Allvac 718Plus	7	As-HT [3]	1174	1005	24.1	30.7	433.1	35.4	226.4	456.1
		+ 760°C/350 Hrs	1073	874	42.2	70.0	453.8	34.0	–	–
Waspaloy	6	As-HT [2]	1087	885	38.6	55.4	430.5	27.8	124.0	–
		+ 760°C/350 Hrs	998	768	39.2	66.2	259.3	36.7	–	–

1. Heat Treatment-Alloy 718: 954°C x 1 hr, AC + 718°C x 8 hrs, FC at 55°C/h to 621°C + 621°C x 8 hrs, AC
2. Heat Treatment-718Plus: 954°C x 1 hr. AC + 788°C x 2 hrs, FC at 55°C/h to 650°C + 650°C x 8 hrs, AC.
3. Heat Treatment-Waspaloy: 1018°C x 1 hr, WQ + 843°C x 8 hrs, AC + 760°C x 16 hrs, AC.

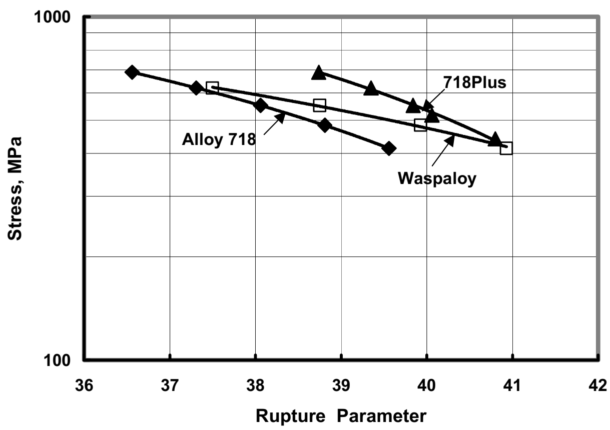
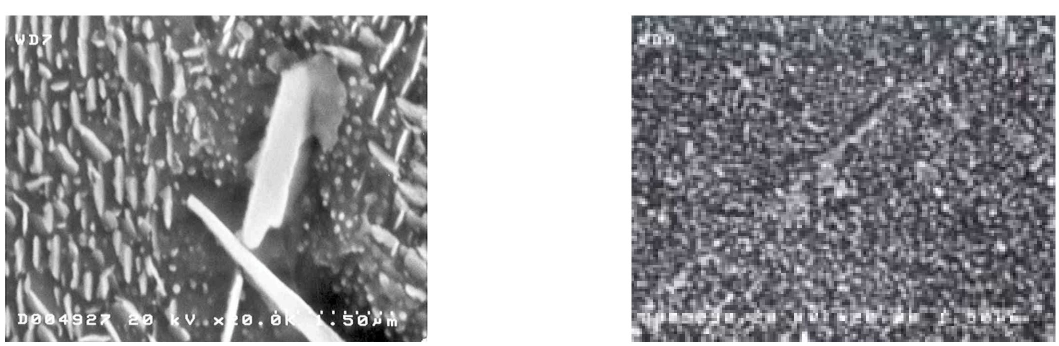


Fig. 11. Larson-Miller plot of stress rupture life of Alloy 718Plus in comparison with Alloy 718 and Waspaloy.



(a) Alloy 718 (b) Allvac® 718Plus™

Fig. 12. Microstructure of Alloy 718 and Allvac® 718Plus™ subjected to 350 hrs thermal exposure at 760°C.

with fine, spherical precipitates in Alloy 718Plus. The predominant precipitate in Alloy 718Plus in both the as-heat treated and long-term exposed conditions has been identified as Nb-containing γ' phase by TEM and XRD. The improved stability is believed to be due to the high Al/Ti ratio retarding transformation of γ' to δ phase, the slow growth kinetics of γ' and low diffusivity promoted by Nb and possibly W partitioning to the γ'. It has been demonstrated, based on numerous trials, that this alloy has processing characteristics similar to Alloy 718 and better than Waspaloy. Alloy 718Plus appears to be an attractive candidate to replace Alloy 718 or Waspaloy in applications that exceed the temperature capability of Alloy 718.

Summary and Conclusions

The role of alloying elements Al, Ti, Nb, Co, Fe, W, Mo, P and B in 718-type alloys were evaluated by modeling calculations and experimental studies with the aim of developing a 718 + 55°C (100°F) alloy with γ' being the dominant precipitation phase. The following conclusions can be drawn from this study:

- With increasing Al+Ti content of Alloy 718, the volume fraction of γ' phase increased at the expense of γ" phase and the alloy became predominantly γ' phase strengthened when Al+Ti content was higher than 3 at%. The thermal stability of mechanical properties and microstructure was significantly improved.

- Al/Ti ratio had the greatest influence on its thermal stability. With decreasing Al/Ti ratio the thermal stability decreased, as shown by massive formation of δ and η phases and significant degradation of mechanical properties after long-term thermal exposure. Modification in matrix elements had little effect on this behavior.

- The best combination of mechanical properties and thermal stability occurred at the Al+Ti level of about 4 at% and Al/Ti (at%) ratio of about 4 for γ'- strengthening Alloy 718. The same held for alloys with modifications in matrix elements.

- Increasing optimum Nb levels led to a stronger alloy, most likely due to the increased content of the strengthening phase. However, excess Nb caused low stress rupture ductility and forging cracking. The optimum content was about 5.5% for alloys with optimum Al and Ti levels.

- Adding Co to 718-type alloys significantly improved stress rupture properties and enhanced the thermal stability for both tensile and rupture. The strengthening effect of Co saturated above 9%.

- There was an optimum Fe level at about 10% where the thermal stability and stress rupture properties peaked. The mechanism for this behavior is not yet clear and requires further study.

- The Mo content of Alloy 718 of about 2.8%, combined with a small W addition of about 1% generated the best combination between mechanical properties and stability. Higher W additions appeared to cause low rupture ductility.

- Elevated P and B levels improved stress rupture properties of Alloy 718Plus. P displayed the larger effect with an optimum amount of about 0.014%P. This can be a cost effective means of improving rupture properties, but the effect on other concerns, such as weldability, requires further evaluation.

- A new alloy, 718Plus, was developed from this study. This alloy has a 55°C (100°F) higher temperature capability than Alloy 718 and mechanical properties and thermal stability equal to or better than Waspaloy up to at least 704°C.

References

1. J.K. Tien, et al, *Proceedings of the 1990 High Temperature Materials for Power Engineering Conference*, ed. E.B. Bachelet, et al. (Kluwer Academic Publisher, 1990), 1341-1356.

2. J.P. Collier, A.O. Selius and J.K. Tien, *Superalloys 1988*, edited by S. Reichman et al., TMS, 1988, 43-52.

3. J.P. Collier, S.H. Wong, J.C. Phillips and J.K. Tien, *Metall. Trans. A*, 1988, Vol. 19A, 1657-1666.

4. J.A. Manriquez, P.A. Bretz, L. Rabenberg and J.K. Tien, *Superalloys 1992*, edited by S. D. Antolovich, et al., TMS, 1992, 507-516.

5. R. Cozar and A. Pineau, *Metall. Trans.*, Vol. 4, 1973, 47-59.

6. E. Andrieu, R. Cozar and A. Pineau, *Superalloy 718 – Metallurgy and Applications*, edited by E.A. Loria, TMS, 1989, 241-256.

7. E. Andrieu, N. Wang, R. Molins and A. Pineau, *Superalloys 718, 625, 706 and Various Derivatives*, edited by E.A. Loria, TMS, 1994, 695-710.

8. K.M. Chang, US Patent 4,981,644, Jan. 1, 1991.

9. K.M. Chang and A.H. Nahm, *Superalloy 718 – Metallurgy and Applications*, edited by E.A. Loria, TMS, 1989, 631-645.

10. R.E. Schafrik et al., *Superalloys 718, 625, 706, and Various Derivatives*, ed. By E.A. Loria, 2001, 1-11.

11. W.D. Cao and R.L. Kennedy, *Superalloys 718, 625, 706 and Various Derivatives*, ed. E.A. Loria, (TMS 2001), 477-488.

12. W.D. Cao and R.L. Kennedy, *Superalloys 718, 625, 706 and Various Derivatives*, ed. E.A. Loria, (TMS 1994), 463-477.

13. W.D. Cao and R.L. Kennedy, *Superalloys 718, 625, 706 and Various* Derivatives, ed. E.A. Loria, (TMS 1997), 511-520.

14. B.H. Kear and D.P. Pope, *Superalloys, Supercomposites and Superceramics*, ed. J.K. Tien and T. Caulfield, Academic Press, Inc., 1989, 545-582.

15. R.V. Miner, *Metall. Trans A*, 1997, Vol. 28A, 1011-1020.

16. S.J. Patel and G.D. Smith, Niobium, *Science & Technology*, ed. P.J.P. Bordignon et al. (TMS 2001), 1081-1108.

17. JMatPro 2.0, Thermotech Ltd/Sente Software Ltd, 2002.

18. N.L Richards and M.C. Chaturvedi, *Inter. Mater. Reviews*, Vol. 45, 2000, 109-129.

19. S. Benhaddad, N.L. Richards, U. Prasad, H. Guo and M.C. Chaturvedi, *Superalloys 2000*, eds. T.M. Pollock et al, TMS, 2000, 703-711.