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DEVELOPMENTS IN WROUGHT Nb CONTAINING SUPERALLOYS (718 + 100°F)

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Abstract

Alloy 718, developed and patented by International Nickel Company in 1962, has become the most widely used, superalloy. It is available in all product forms, including ingot, billet, bar, rod, wire, sheet, strip, plate and castings. The alloy's popularity is due to its excellent combination of mechanical properties, moderate price and good processability, including weldability. Its maximum use temperature, however, is restricted to about 1200°F. Above this temperature the γ'' (Ni_3Nb) precipitation hardening phase responsible for the alloy's outstanding properties rapidly overages and properties, particularly creep resistance, fall dramatically.

There has been a substantial amount of work by numerous investigators over the years to increase the temperature capability of 718. But until now, the only commercially significant choices for structural applications above 1200°F were γ' (Ni_3Al, Ti) hardened alloys such as Waspaloy® and Rene'® 41. These alloys, however, are more costly and difficult to fabricate and weld than 718.

This paper reviews some of the past efforts to improve the performance of 718-type alloys, including current work by Allvac on a newly developed alloy, Allvac® 718Plus™. The chemistry, mechanical properties and processing characteristics of alloy 718Plus will be compared in detail to both 718 and Waspaloy and the relative cost of these alloys will be discussed. Data will be presented from full scale, production sized ingots which show a 100°F temperature advantage for 718Plus alloy over 718, while maintaining its good processing characteristics.

Introduction

Alloy 718 is without a doubt the most famous superalloy. It is the most widely researched and used of all superalloys. It was reported in 1989 that 718 comprised 45% of the total tonnage of wrought and 25% of cast nickel-based alloys[1]. Based on the comments of GE[2] and Pratt & Whitney[3], today's usage likely exceeds 60% of total superalloy consumption. The alloy even has its own dedicated symposium, "Superalloy 718 Metallurgy and Applications," originated in 1989 although other Nb containing superalloys are now part of the agenda. Alloy 718 is produced in almost every conceivable mill form, and made into innumerable forged, cast or fabricated final components for a variety of markets. The alloy owes this popularity to its unique combination of mechanical properties, moderate cost due to its chemistry (18% Fe), good hot workability, and being the most weldable[4] of all the Ni-based superalloys.

Use temperature for alloy 718 is restricted to 1200°F due to the rapid overaging of the predominate strengthening phase, γ" (Ni_3Nb) and transformation to coarse, stable δ phase (Ni_3Nb) which has little strengthening effect. When exposed to 1300°F for 5000 hours, the tensile yield strength decreases by 40%[5]. Allvac data suggests that time dependent properties such as stress rupture and creep drop even more[6]. Numerous people over many years have pointed out that it would be very desirable to increase the use temperature of alloy 718 by a significant amount, e.g. 100°F, while at the same time retaining the principal attributes of the alloy: high strength, weldability and moderate cost.

Compositional Modifications of 718

There are many studies in the literature showing improved microstructural stability and better property retention after long time, high temperature exposure for 718-type alloys with changes in Al, Ti and Nb. Cozar & Pinean[7] raised the (Al + Ti)/Nb ratio and also developed the compact morphology heat treatment. Collier, et al.[8,9] and Guo, Xu and Loria[10,11,12] extended this work. Braun and Radavich[13] showed improved stability and higher solution temperatures resulting from the complete substitution of Ta for Nb in 718. None of these modifications showed property improvements of the desired magnitude. Chang and Nahm[14] added 3% Ta and 12% Co and eliminated all of the Fe resulting in a commercial alloy Rene' 220 which has been used in castings. The alloy was highly weldable and had a 100°F temperature advantage in stress rupture over 718 but had very high elemental raw material cost and property issues in wrought form. Pratt & Whitney developed PWA 1472, a high strength casting alloy modification with increased Nb & Ti[3]. There is no published data on its maximum use temperature but based on the results of previous investigators discussed above, it is highly unlikely the temperature capability would be significantly increased over 718. Rolls Royce developed a weldable casting alloy, RS-5, with increased temperature capability but much lower tensile strength than 718[15]. Chemistry and properties suggest it is more like a Nb, Ta modified Waspaloy than 718. Cao and Kennedy[16] discovered the beneficial effect of P&B additions on stress rupture life and creep rate of 718 but subsequently determined that there was no improvement in thermal stability. Preliminary results on a 9%Co, 1%Ta (replacing Fe), alloy 991 modification have been reported by GE[2], but cost may be an issue. Despite these efforts, there is no commercial alloy in use today which has improved on the use temperature deficiencies of 718 while maintaining its many attributes.

Development of 718Plus Alloy

In 1997 Allvac began an internal program to explore the well tread ground of improving the temperature capability of 718. The objectives of this work were:

- 100°F temperature advantage based on the Larson-Miller, time-temperature parameter
- Improved thermal stability; equal to Waspaloy at 1300°F
- Good weldability; at least intermediate to 718 and Waspaloy
- Minimal cost increase; intermediate to 718 and Waspaloy
- Good workability; better than Waspaloy

Following the efforts with P&B additions reported in reference 4, Cao initiated studies investigating modifications in the precipitation hardening elements Al, Ti and Nb in combination with trace elements P&B. Based on these results, studies were extended to include matrix modifying elements Fe, Co and W. All of the work was performed on 50 to 300-lb pilot plant heats produced by vacuum induction melting followed by vacuum arc remelting to produce 4” to 8” diameter ingots. Ingots were homogenized, forged, rolled and heat treated using standard 718 practices to provide test material. From the beginning of this program, thermal stability after long time exposure to temperatures of at least 1300°F was used as a key screening requirement. Partial results of the Al, Ti, Nb and B,P effects have been published in reference 6. The balance of this work and the effects of matrix element changes will be presented in September at Superalloys 2004[17].

The optimum chemistry from this program effort, considering the sometimes contradictory objectives, has been designated as Allvac® 718Plus™. This composition compared to nominal 718 and Waspaloy chemistries is shown in Table 1.

Table 1. Chemistry Comparison of Alloy 718, Allvac® 718Plus™ and Waspaloy

Alloy	Chemistry											
	C	Ni	Cr	Mo	W	Co	Fe	Nb	Ti	Al	P	B
718	0.025	B	18.10	2.80	–	–	18.00	5.40	**1.00**	**0.45**	**0.007**	0.004
718Plus	0.020	B	18.00	2.75	**1.0**	**9.0**	**10.00**	5.45	**0.70**	**1.45**	**0.014**	0.004
Waspaloy	0.035	B	19.40	4.25	–	**13.25**	–	–	**3.00**	**1.30**	**0.006**	0.006

The principal differences in 718Plus alloy chemistry compared to 718 are the increase in total Al+Ti content, Al/Ti ratio, the addition of Co and W, replacing mainly Fe, and the purposeful additions of a small amount of P.

Properties

Tensile and Rupture

The mechanical properties of 718Plus alloy are very attractive in comparison to 718 and Waspaloy up to a temperature of at least 1300°F. Tensile and stress rupture properties presented in this paper were taken from 8” diameter bar for alloy 718Plus and 3/4 x 5” bar for both 718 and Waspaloy. These data are typical of the 718Plus alloy results from a number of pilot plant and industrial heats. Tensile results, summarized in Table 2, show that the properties of alloy 718Plus are comparable to 718 at room temperature and higher at 1200°F and 1300°F. Tensile strength of 718Plus alloy also exceeds that of Waspaloy from room temperature to 1300°F. Waspaloy, however, is not a particularly high tensile strength alloy by comparison to 718. Tensile ductilities are very good over the entire temperature range.

Stress rupture and creep property comparisons are shown in Table 3. Rupture life and creep resistance of 718Plus alloy is far superior to that of 718 at 1300°F. Rupture life for Waspaloy is the same as 718Plus alloy at 1300°F, but limited creep testing shows slightly improved creep resistance at 1300°F for 718Plus alloy. Stress rupture ductility for 718Plus alloy is also excellent.

Table 2. Tensile Properties of Alloy 718, Allvac® 718Plus™ and Waspaloy

Alloys	GS	Heat Treat	Tensile Properties 68°F YS Ksi	UTS Ksi	El %	Ra %	1200°F YS Ksi	UTS Ksi	El %	Ra %	1300°F YS Ksi	UTS Ksi	El %	Ra %
Alloy 718	6	A	174.3	211.6	20.2	40.6	146.2	164.4	20.8	28.3	135.8	147.2	20.3	27.5
718Plus	7	B	174.7	218.8	21.9	35.7	148.4	189.3	23.7	27.3	145.8	170.3	24.1	30.7
Waspaloy	6	C	157.6	209.0	27.0	45.4	142.0	194.6	22.8	32.0	128.3	157.7	38.6	55.4

A. Standard 718 Heat Treatment: 1750°F/1 hr/AC+1325°F/8 hrs/FC 100°F/hr to 1150°F/8 hrs/FC
B. 1750°F/1 hr/AC+1450°F/2 hrs/FC 100°F/hr to 1200°F/8 hrs/FC
C. Standard Waspaloy Heat Treatment: 1865°F/1 hr/WC+1550°F/4 hrs/AC+1400°F/16 hrs/AC

Table 3. Stress Rupture and Creep Properties of Alloy 718, Allvac® 718Plus™ and Waspaloy

Alloy	GS	Heat Treat	1300°F/80 Ksi Life, hrs	El %	Creep 1300°F/70 Ksi $t_{0.1}$, hrs	$t_{0.2}$, hrs	Creep Rate
Alloy 718	6	A	157.9	19.5	16.5	29.0	8.70×10^{-5}
718Plus	7	B	433.1	35.4	81	226.4	6.88×10^{-6}
Waspaloy	6	C	430.5	27.8	79.1	124.0	2.20×10^{-5}

A. Standard 718 Heat Treatment: 1750°F/1 hr/AC+1325°F/8 hrs/FC 100°F/hr to 1150°F/8 hrs/FC
B. 1750°F/1 hr/AC+1450°F/2 hrs/FC 100°F/hr to 1200°F/8 hrs/FC
C. Standard Waspaloy Heat Treatment: 1865°F/1 hr/WC+1550°F/4 hrs/AC+1400°F/16 hrs/AC

Stress rupture results for all 3 alloys plotted as Larson-Miller curves are shown of Figure 1. The lower sloped curve for Waspaloy suggests that its properties would be better than those of 718Plus at higher temperatures (>1300°F) as might be expected. Data published in the *Aerospace Structural Metals Handbook* was used to generate the curves for 718 and Waspaloy. The two data points available for 718Plus lie almost exactly on top of the alloy 718 line plus 100°F.

Thermal Stability

Thermal stability of 718Plus alloy has been extensively tested by exposing fully heat treated samples to long time exposures at temperature. Initially 1300°F for up to 1000 hours was used but more recent testing has been done at 1400°F for 100 and 350 hours to shorten the test time. Results show the thermal stability of 718Plus alloy is far superior to 718 and at least as good as Waspaloy under the conditions tested. The change in 1300°F tensile strength with 1400°F exposure time for all three alloys is shown in Figure 2. It is clear from these data that there is a relatively small change in 718Plus alloy and Waspaloy compared to 718. The effect of thermal exposure on rupture life is presented in Figure 3. In this case, the rupture life of 718Plus and Waspaloy actually increased after 100 hours, then dropped slightly to close to the as-heat treated values. This perhaps suggests that the initial heat treat conditions were actually slightly underaged. The strength of alloy 718, in contrast, drops significantly after 100 hours and has almost no residual rupture life remaining after 350 hours exposure. Creep test comparisons following thermal exposure show similar losses with creep life dropping to less than one-tenth of pre-exposed levels following 1000 hours at 1300°F. Ductility of 718Plus alloy for both the tensile and rupture tests is not degraded by thermal exposure and typically increases following exposure.

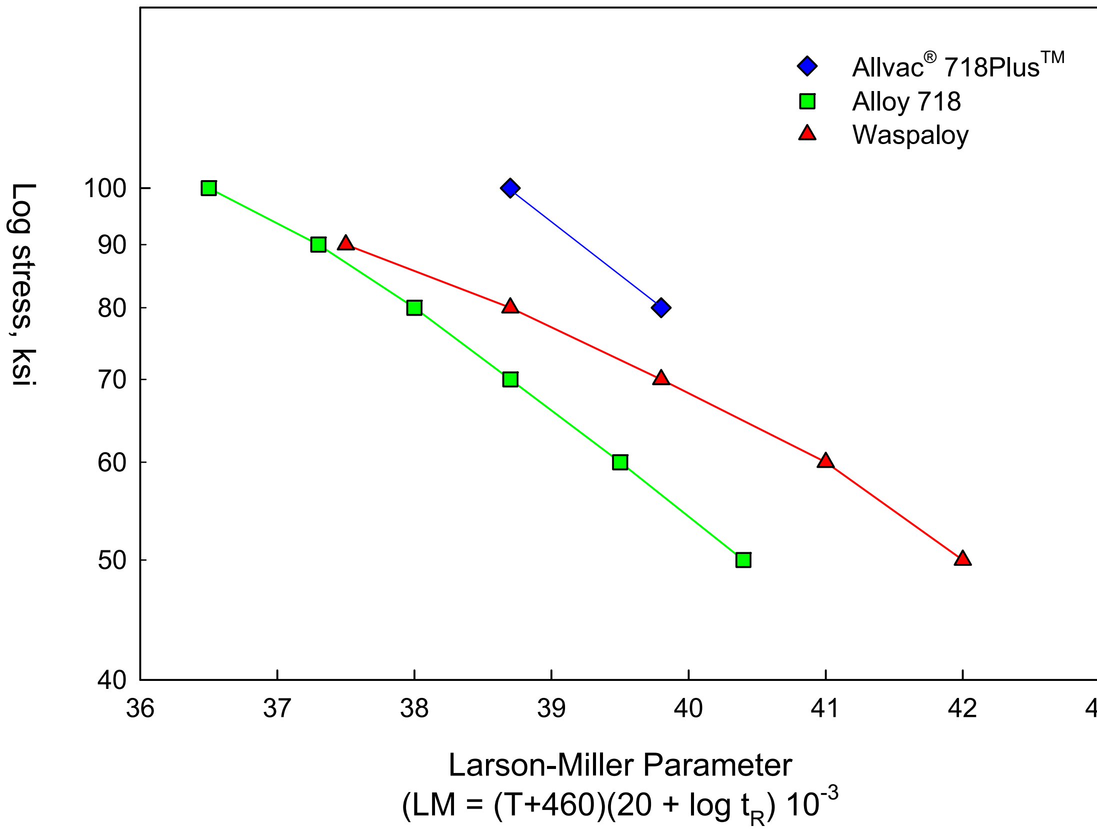


Figure 1. Larson-Miller Stress Rupture Life Comparison

The improved stability evidenced in alloy 718Plus mechanical properties is also really apparent upon examination of the microstructure of thermally exposed bars. Figure 4 shows SEM microstructures of 718 and 718Plus alloys following 350 hour heat treatment at 1400°F. Alloy 718 shows extensive coarsening of γ" precipitates and large amounts of δ phase following exposure while very little precipitate coarsening is obvious in 718Plus alloy. The precipitate phase visible in 718Plus alloy is believed to be γ'.

Casting

Alloy 718Plus was developed principally as a wrought alloy, but the fact that 718 is so widely used in cast form prompted a small casting investigation. Cast-to-size test bars were prepared by Howmet Research Corporation from melt stock supplied by Allvac. Two wax pattern assemblies of 18 bars each, 5/8" diameter by 6" long, were cast using standard equiax foundry procedures. The bars were given a HIP cycle of 2125°F-15ksi for three hours and x-ray inspected. Castability was judged to be good as all bars filled completely on the first pour and were x-ray defect free. Preliminary tensile and rupture test results are shown in Table 4. All data for 718Plus alloy far exceed the minimum property requirements of AMS specification 5383D for cast 718. Work is in progress to optimize the heat treatment condition and chemistry for the cast version of 718Plus alloy. Results will also be compared to properties of two advanced Nb containing casting alloys, Rene' 220 and RS5 over which 718Plus alloy would have a substantial raw materials cost advantage.

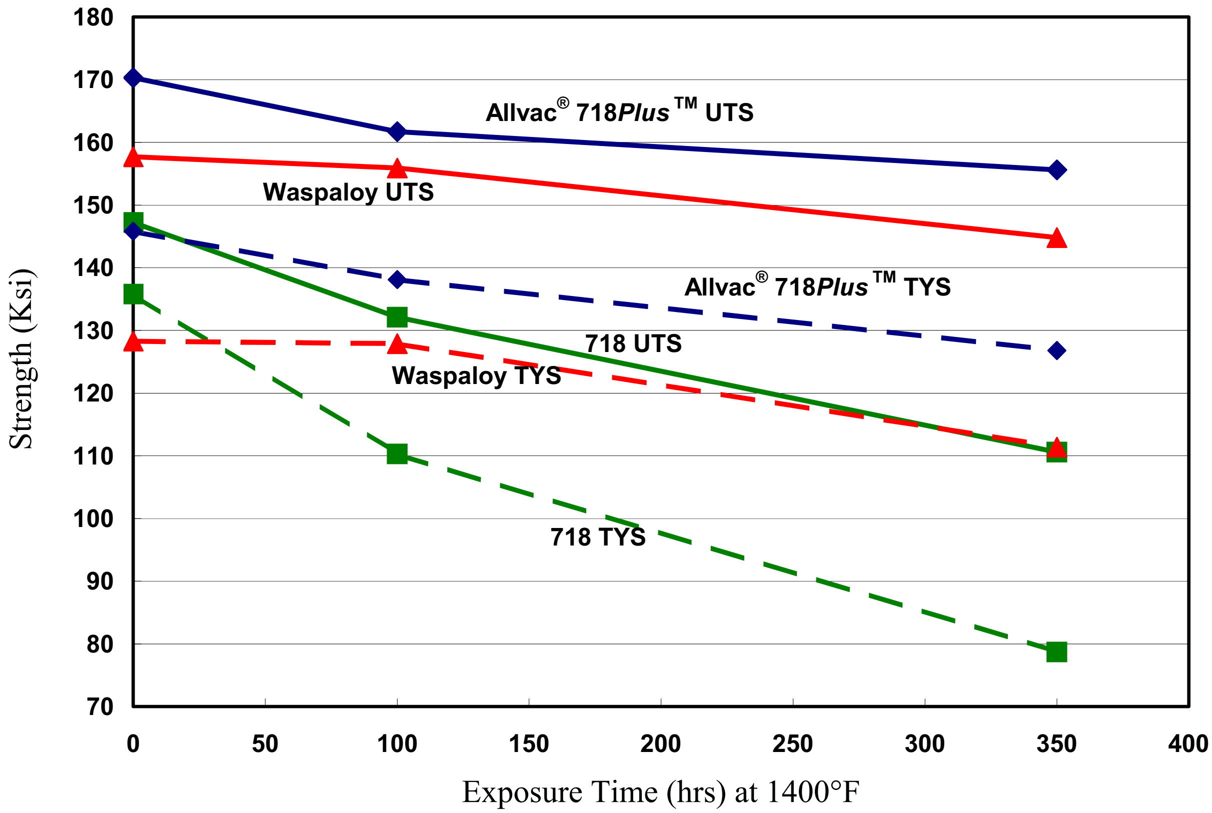


Figure 2. Effect of Thermal Exposure on Ultimate Tensile and Yield Strength at 1300°F

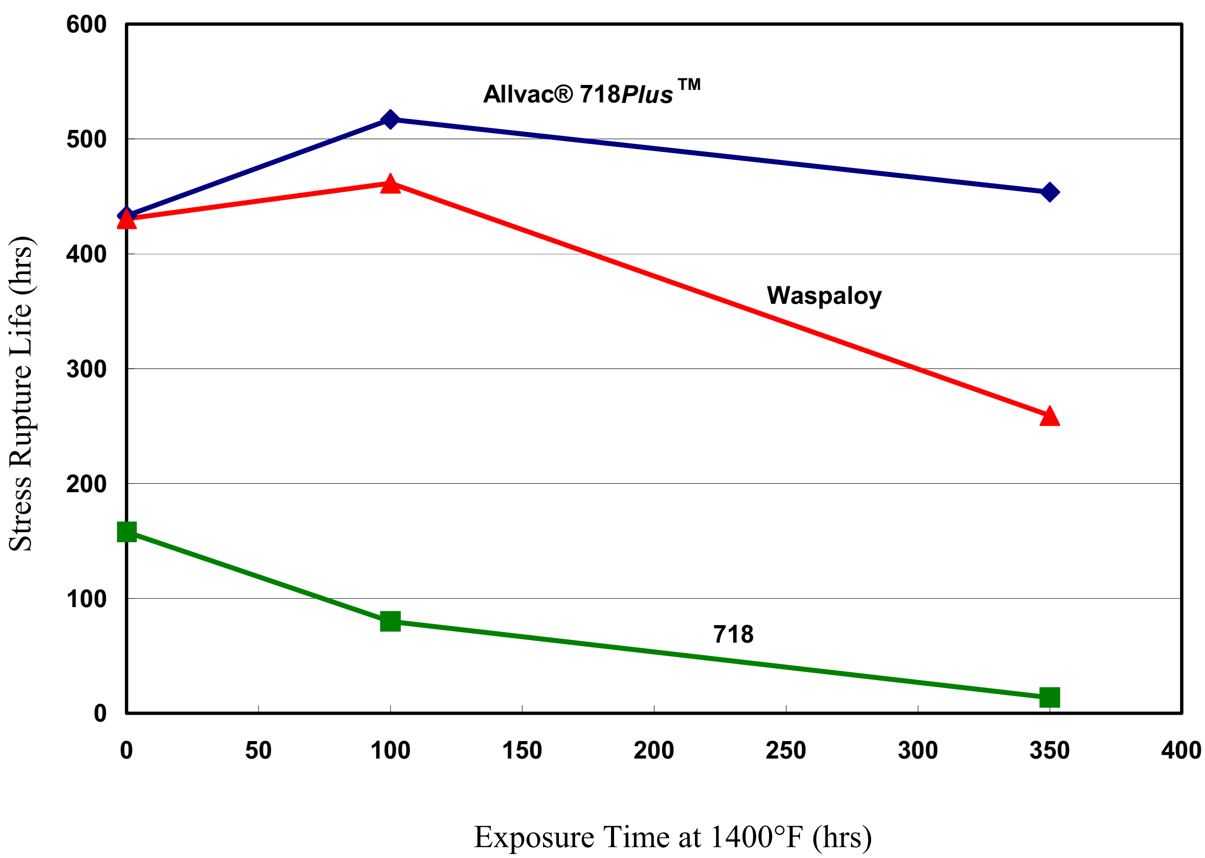
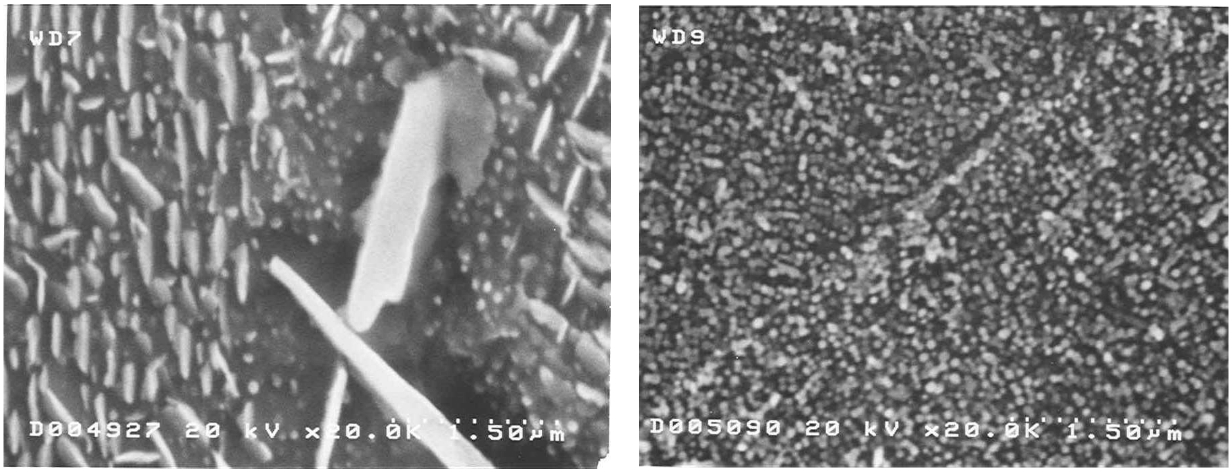


Figure 3. Effect of Thermal Exposure on Rupture Life at 1300°F/80 ksi.



(a) (b)

Figure 4. Microstructure of (a) Alloy 718 and (b) Allvac® 718Plus™ after 350 Hours of Thermal Exposure at 1400°F. (Original magnification 20,000x).

Table 4. Properties of investment cast and HIPped Allvac® 718Plus™ test bars

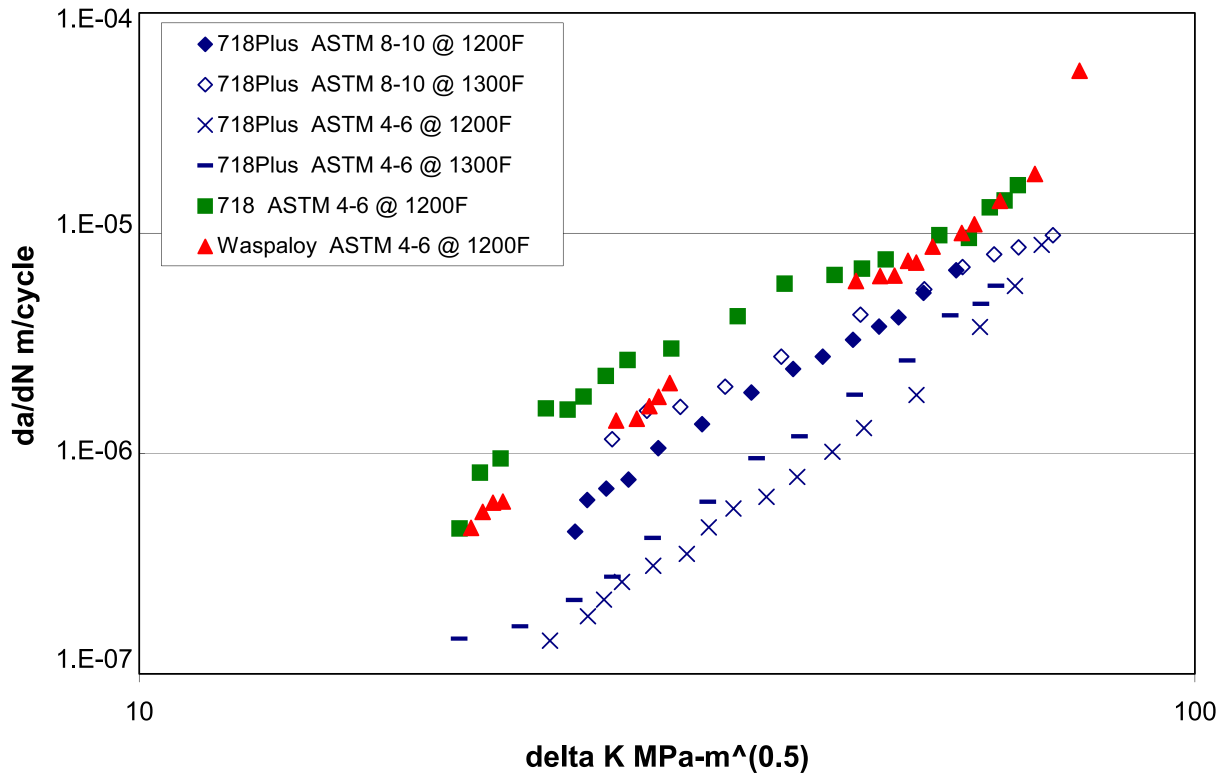
		68°F Tensile				1300°F Tensile				1300°F Stress Rupture
Alloy	Heat Treat	YS ksi	UTS ksi	EL %	RA %	YS ksi	UTS ksi	EL %	RA %	Stress/Life HRS
718Plus	A	119-132	162-179	10-24	9-32	95-101	117-142	14-16	15-20	90/45-111
AMS 5383D (718)	B	110	125	5	10					65/23

A. 1750°F/1 hr/AC+1450°F/2 hrs/FC 100°F/hr to 1200°F/8 hrs/FC
B. Standard 718 Heat Treatment: 1750°F/1 hr/AC+1325°F/8 hrs/FC 100°F/hr to 1150°F/8 hrs/FC

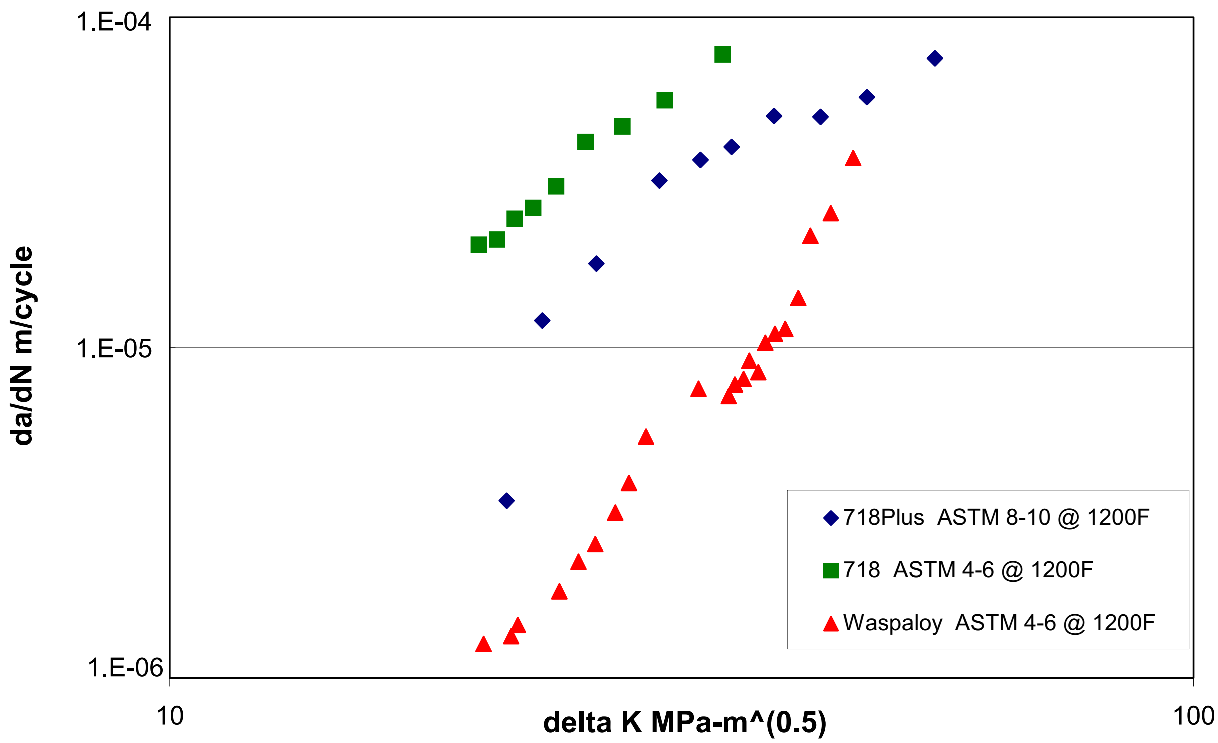
Fatigue Crack Growth

Fatigue crack growth rate (FCGR) testing of 718Plus alloy, again compared to 718 and Waspaloy, has been completed by the University of West Virginia. Rolled plates were prepared to produce both fine (ASTM 8-10) and intermediate (ASTM 4-6) grain sizes. Testing was performed at 1200°F and 1300°F with zero and 100 second hold times. Zero hold time results are shown in Figure 5a. Crack growth rates for 718Plus alloy were lower than for either 718 or Waspaloy. In fact, crack growth rates for 718Plus alloy with both the fine and intermediate grain sizes and at both 1200°F and 1300°F exceeded results for 718 and Waspaloy intermediate grain size results at 1200°F.

Data with the 100 second hold time are plotted in Figure 5b. Under these test conditions 718Plus alloy results exceed those of 718 but are not as good as Waspaloy. It is believed that the amount and morphology of delta phase precipitation plays a key role in fatigue crack growth and is being investigated further. A detailed report of this work will be presented at Superalloys 2004[18].



(a)



(b)

Figure 5. Fatigue Crack Growth Rate of Allvac® 718Plus™ Alloy, 718 and Waspaloy at no hold time (a) and 100 second hold time (b).

Processing

During the six years of this development effort, multiple pilot plant ingots in the 4 to 8" diameter size range have been melted and forged at Allvac. In addition, two 17" diameter x 3000 pound heats have been VIM and VAR melted and forged and rolled to a variety of product sizes from 8" to 5/8" diameter bar. Processing schedules have been similar to those used for 718. Hot workability, yields, macro inspection and ultrasonic results have all been good. A 35" OD rolled ring was also produced courtesy of Firth Rixson Viking (Figure 6). Starting with 8" diameter billet the ring was upset, punched and rolled to final size without the intermediate conditioning normally required for Waspaloy. The rolling schedule was similar to a standard cycle used for 718 but employed fewer reheats. Workability was judged to be excellent. Most recently, a full scale production heat was melted. Both double melt and triple melt 20" diameter ingots were produced. Both ingots have been successfully converted to 10" diameter billet. Figure 7 is a macro disk of one of the 10" diameter billets. It shows a uniform, fine grain structure and a complete absence of any macro defects. Tensile and rupture test results taken directly at-size from the 10" billet are very similar to the 8" diameter data presented in Tables 3 and 4. All process results to date suggest alloy 718Plus behaves very similar to 718 and is much easier to hot work than Waspaloy.

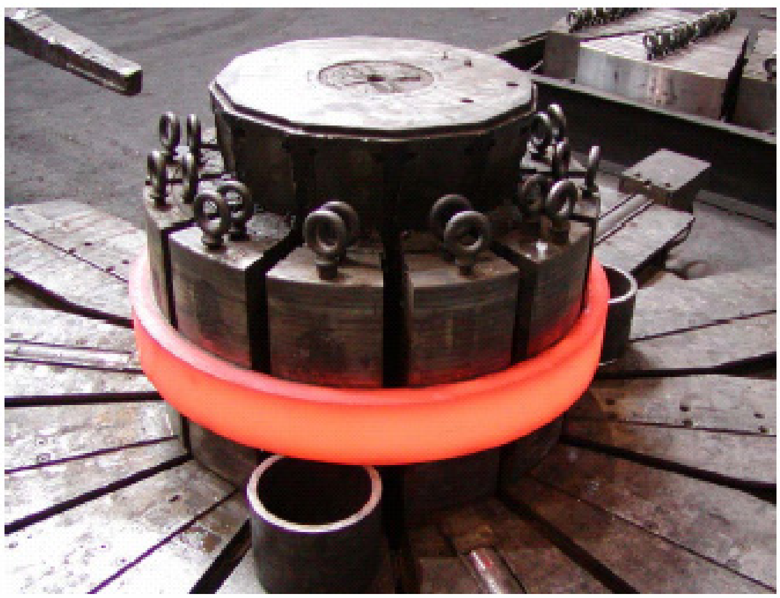


Figure 6. Seamless Rolled Ring of Allvac® 718Plus™ Alloy (Courtesy of Firth Rixson Viking)

Limited weldability testing has been conducted on 718Plus alloy to date but results have been encouraging. Sample fillerless fusion, TIG weld beads were prepared on alloy 718Plus, 718 and Waspaloy, followed by sectioning and metallographic examination. Multiple cracks were found in the Waspaloy sample but none were observed in either 718Plus alloy or 718. A detailed weldability test program comparing the same three alloys has been initiated with the University of Manitoba. Testing will consist of weld bead cracking tests using both TIG and EB and Gleeble testing for nil-ductility and ductility recovery temperatures. Results will be reported at a later date.

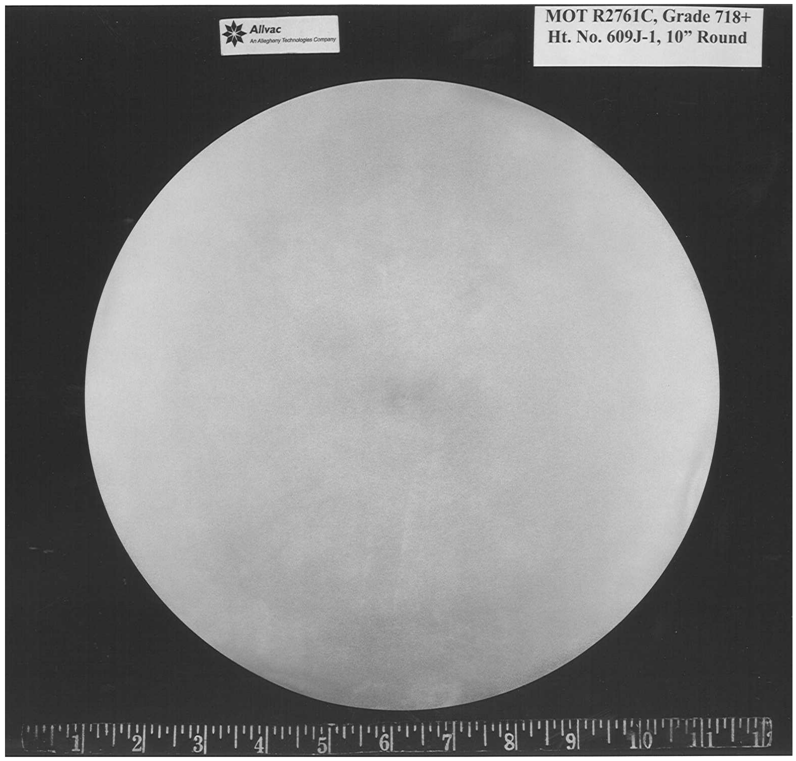


Figure 7. Macro Disk of 10" Diameter Allvac® 718Plus™ Billet.

Cost

The cost of 718Plus alloy is expected to be intermediate to 718 and Waspaloy. Cost will be lower than Waspaloy due to lower intrinsic raw material value, improved hot workability (greater yield), and ease of fabrication (weldability). Alloy 718Plus contains Fe and less Co than Waspaloy providing it an advantage in raw material cost. However the true value may come from the cost savings observed at the forgers and fabrication shops. Initial forgings on 718Plus alloy showed a substantial reduction in cycle time compared to Waspaloy rings due to fewer number of reheats required and no in-process grinding to remove surface cracking. Waspaloy required multiple reheat cycles and had a 5% yield loss from grinding between forging steps. Alloy 718Plus will provide a cost savings over Waspaloy in production of static structures due to its ability to be welded and well repaired without suffering from weld induced cracking.

Conclusions

A multi year development effort at Allvac has identified a new alloy, 718Plus, which appears to have achieved the long sought after goal of increasing the temperature capability of 718 by 100°F without sacrificing its other attractive features. Most mechanical properties of 718Plus alloy are superior to both 718 and Waspaloy up to 1300°F. The alloy has excellent thermal stability, comparable to Waspaloy at 1300°F. Fabricability including weldability of this alloy appears to be very similar to 718 and much better than Waspaloy. Costs for 718Plus alloy components should be intermediate to 718 and Waspaloy. As the trend continues to higher operating temperatures in turbine engines it appears that alloy 718Plus should be an attractive replacement for 718. The alloy would be suitable for any part currently made from 718 including, rings, cases, disks, blades, shafts, fasteners and structural castings.

References

[1] E.A. Loria, Preface from Superalloy 718-Metallurgy & Applications, ed. by E.A. Loria, TMS, 1989, p. v.
[2] R.E. Schaferik, D.D. Ward and J.R. Groh, "Application of Alloy 718 in GE Aircraft Engines: Past Present and Next Five Years," Superalloy 718-Metallurgy & Applications, ed. by E.A. Loria, TMS, 1989, p. 1-11.
[3] D.F. Paulonis and J.J. Schirra, "Alloy 718 at Pratt & Whitney – Historical Perspective and Future Challenges," Superalloys 718, 625, 706 & Various Derivatives, ed. by E.A. Loria, TMS, 2001, p. 13-23.
[4] A. Lingenfelter, "Welding of Inconel Alloy 718: A Historical Overview," Superalloy 718-Metallurgy & Applications, ed. by E.A. Loria, TMS, 1989, p. 673-683.
[5] S. Mannan, S. Patel and J. deBarbadillo, "Long Term Stability of Inconel Alloys 718, 706, 909 and Waspaloy at 593°C and 704°C," Superalloys 2000, ed. by T.M. Pollack, et al.., TMS, 2000, p. 449-458
[6] W.D. Cao and R.L. Kennedy, "Improving Stress Rupture Life of Alloy 718 by Optimizing Al, Ti, P and B Contents," Superalloys 718, 625, 706 & Various Derivatives, ed. by E.A. Loria, TMS, 2001, p. 477-488.
[7] R. Cozar and A. Pinean, "Morphology of γ' and γ" Precipitates and Thermal Stability of Inconel 718 Type Alloys," *Met. Trans*, V4, 1973, p. 47-59.
[8] J.P. Collier, S.H. Wong, J.C. Phillips and J.K.Tien, "The Effect of Varying Al, Ti and Nb Content on Phase Stability of Inconel 718," *Met Trans*, V19A, 1988, p. 457-1666.
[9] J.P. Collier, A.O. Selius and J.K. Tien, "On Developing a Microstructurally & Thermally Stable Iron-Nickel Base Superalloy," Superalloys 88, TMS, 1988, p. 43-52.
[10] E. Guo, F. Xu and E.A. Loria, "Improving Thermal Stability of Alloy 718 via Small Modifications in Compositions," Superalloy 718-Metallurgy & Applications, ed. by E.A. Loria, TMS, 1989, p. 567-576.
[11] E. Guo, F. Yu and E.A. Loria, "Further Studies on Thermal Stability of Modified 718 Alloys," Superalloys 718, 625, 706 & Various Derivatives, ed. by E.A. Loria, TMS, 1994, p. 721-734.
[12] F. Yu, E. Guo, E.A. Loria and P. Zhang, "Thermal Stability of Modified 718 Alloys Aged 2000 Hours at 700°C," Superalloys 718, 625, 706 & Various Derivatives, ed. by E.A. Loria, TMS, 1997, p. 503-509.
[13] A.R. Braun and J.F. Radavich, "A Microstructural and Mechanical Properties Comparison of P//M 718 and P/M TA718," Superalloy 718-Metallurgy & Applications, ed. by E.A. Loria, TMS, 1989, p. 623-630.
[14] K.M. Chang and A.H. Nahm, "Rene 220: 100°F Improvement Over Alloy 718," Superalloy 718-Metallurgy & Applications, ed. by E.A. Loria, TMS, 1989, p. 631-645.
[15] R.G. Snider, "Nickel Base Alloys for Castings," U.S. Patent No. 5,330,771, 1994.
[16] W.D. Cao and R.L. Kennedy, "Thermal Stability of Alloys 718 and Allvac 718-ER® Alloy," Superalloys 718, 625, 706 & Various Derivatives, ed. by E.A. Loria, TMS, 2001, p. 455-464.
[17] W.D. Cao and R. Kennedy, "Role of Chemistry in 718 Type Alloys – Allvac 718Plus™ Development," to be presented at Superalloys 2004, TMS.
[18] X. Lu, S. Rangaragan, E. Barbero, K. Chang, W.D. Cao, R. Kennedy and T. Carniero, "Fatigue Crack Propagation of Newly Developed 718Plus™ Superalloy," to be presented at Superalloys 2004, TMS.