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ALLVAC® 718PLUS™, SUPERALLOY FOR THE NEXT FORTY YEARS

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Abstract

Allvac® 718Plus™ alloy is a new nickel base superalloy, offering excellent mechanical properties, increased temperature capability, good fabricability and moderate cost. This highly desirable combination of characteristics positions the alloy to very effectively fill the longstanding gap between the two most widely used wrought superalloys, 718 and Waspaloy.

This paper will review the development of alloy 718Plus, which has progressed over the last eight years, including the effects of chemistry, heat treatment, processing and structure on mechanical properties. The current production status and capability of the alloy will also be discussed along with ongoing applications development. Comparisons will be made to 718, Waspaloy and other superalloys illustrating that alloy 718Plus is the best available candidate to sustain the advances in engine development made possible by the forty-plus year life of alloy 718.

Introduction

Alloy 718 has had a very long and successful history as was well documented in the keynote papers presented at the Sixth International Symposium on Superalloys 718, 625, 706 and Derivatives in 2001 [1, 2]. The reasons for alloy 718's popularity include excellent strength, good hot and cold workability, the best weldability of any of the superalloys and last, but not least, moderate cost.

As evidenced by this and previous symposia, there has been an enormous amount of work directed at understanding and improving alloy 718. This effort has resulted in a continuous string of improvements in melting and remelting, ingot conversion and forging, heat treatment and inspection. Notable in this regard are triple melting, fine grain billet, direct age (DA) heat treatment, fine grain forgings and very large ingots.

The one limitation of alloy 718 which has not been overcome is its maximum use temperature, commonly given as 649°C. This limit is imposed by the stability of the principal strengthening precipitate, γ''. With prolonged exposure at this temperature or higher, γ'' rapidly overages and transforms to the equilibrium δ phase with an accompanying loss of strength and especially creep life.

Other wrought, commercial superalloys exist which have significantly greater temperature capability such as Waspaloy and René 41. These alloys are typically γ' hardened and are significantly more difficult to fabricate and weld. Because of this and because of their intrinsic raw material content, these alloys are significantly more expensive than alloy 718.

There have been numerous attempts to develop an affordable, workable 718-type alloy with increased temperature capability [1, 3-11]. At the 2001 Superalloys 718 Symposium, it was recognized that the need still existed [1, 2].

After a number of years of systematic work, including both computer modeling and experimental melting trials, ATI Allvac has developed a new alloy, Allvac® 718Plus™, which offers a full 55°C temperature advantage over alloy 718 [12-14]. The alloy maintains many of the desirable features of alloy 718, including good workability, weldability and moderate cost. The alloy development has advanced well beyond the laboratory phase and full production scale products have been made and tested.

This paper will highlight the metallurgy of alloy 718Plus, compare mechanical properties with other superalloys and discuss processing, cost and applications of current interest. Several other papers presented in this conference will discuss many of these subjects in greater detail.

Development Background and Metallurgy

Chemistry

As the name would imply, alloy 718Plus is a derivative of alloy 718. The alloy composition reflects a continuation of work performed at ATI Allvac in the early 1990's directed at improving the creep and rupture properties of alloy 718 by purposeful additions of P and B [15-21]. The resulting improvements were equivalent to about a 20°C increase in temperature capability. This level of increase was insufficient to justify the costs associated with approvals for a new or modified alloy. A temperature capability increase of 55°C is frequently mentioned as a minimum requirement in this regard. With this as a background, an expanded program was begun which included both Pilot Plant melting and computer modeling. Starting from a base 718 alloy composition, the effects of a number of elements on structure, mechanical properties and thermal stability were investigated. Thermal stability was judged to be especially important for a new, higher temperature alloy in light of the well known, extremely rapid overaging demonstrated by alloy 718 at 649°C.

The development began by examining the effects of Al/Ti ratio and Al + Ti content. Modeling results based on JMatPro 2.0 in Table I showed that the volume of γ' increased while γ'' and δ phases decreased as the Al+Ti content and Al/Ti ratio increased. At the Al+Ti and Al/Ti values of alloy 718Plus, nominally four atomic percent, γ' is the predominate precipitation hardening phase. The effect of Al/Ti ratio on stress rupture life and thermal stability of experimental heats is shown in Figure 1. Clearly rupture life and thermal stability increased dramatically as Al/Ti ratio was increased from the value of one for alloy 718 to four or higher, based on atomic %. Thermal stability, expressed as retention ratio, R, was measured by rationing rupture life after extended exposure at high temperature to the value in the as-heat treated condition. It should also be noted that there has been no indication of embrittlement associated with thermal exposure. Tensile and stress rupture ductility either remained constant or increased following exposure for 500 to 1000 hours at 760°C and 732°C, respectively. Similarly the effect of Co additions on rupture life and thermal stability was examined. Results in Figure 2 showed both values peaked at about the 10% Co level.

Table I. Predicted Phase Content at 650°C vs. (a) Al+Ti and (b) Al/Ti Ratio

(a) Al+Ti Content with Al/Ti = 4 at%

Phase Mole %	**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

(b) Al/Ti Ratio with Al+Ti = 4 at%

Phase Mole %	**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

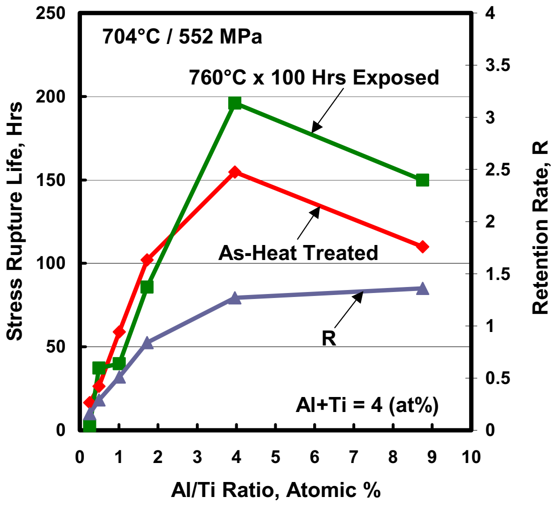


Figure 1. Stress Rupture Life as a Function of Al/Ti Ratio in Alloy 718Plus™.

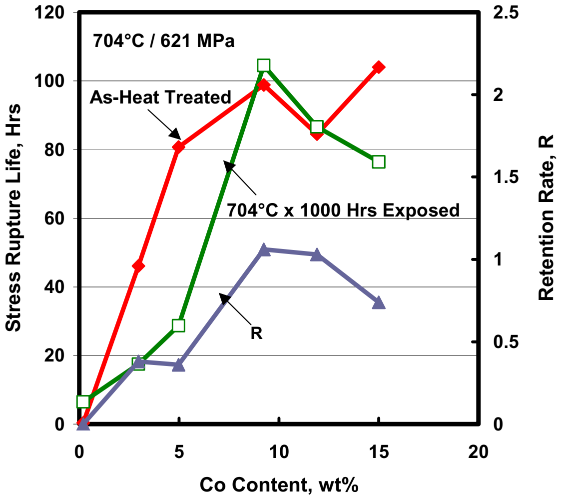


Figure 2. Effect of Co Content on Stress Rupture Life of Alloy 718Plus™.

The effects of Fe, Nb, W, P&B were also tested and results are explained in detail in previously published work [13].

Based on this work, the nominal chemical composition for alloy 718Plus was established as shown in Table II. The chemistry of alloy 718 is shown for comparison purposes with the major chemical element changes shaded.

Table II. Nominal Chemistry Comparison of Alloys 718Plus™ and 718

Alloy	**Chemistry**											
	Ni	**Cr**	**Co**	**Mo**	**W**	**Nb**	**Al**	**Ti**	**Fe**	**C**	**P**	**B**
718	Bal	19	---	3.0	---	5.15	0.6	0.9	18.5	0.04	0.007	0.003
718Plus	Bal	18.0	9.1	2.7	1.0	5.4	1.45	0.75	9.5	0.020	0.006	0.005

Precipitating Phases

The predicted weight percentages at 650°C and transformation temperatures for the phases which most influence properties are shown in Table III. Alloy 718Plus has a much larger content of γ’ and γ” than alloy 718 and a smaller amount of δ phase. Solvus temperatures for γ’ and γ” are also higher in alloy 718Plus. All of these points likely contribute to improved high temperature properties. These predicted values for γ’ plus γ” content for both alloys are in reasonable agreement with values measured by Xie, *et al.* [22]. Measured values for δ phase solvus in alloy 718Plus are in the range of 1000°C to 1020°C.

Table III. Model Predictions of Principal Phases at 650°C and Transformation Temperatures for Alloys 718 and 718Plus™

Phase		718		718Plus	
		wt%	°C	wt%	°C
With (δ)	δ	12.2	1027	9.93	1065
	γ’	7.8	883	19.7	995
Without (δ)	γ”	10.4	946	6.64	968
	γ’	9.6	909	23.2	1002

One of the major differences between alloy 718 and Waspaloy is the speed of the precipitation reaction. The γ” precipitation in alloy 718 is very sluggish and accounts in part for the good weldability and processing characteristics of the alloy. Figure 3 shows the aging response for alloy 718Plus lies between that for alloy 718 and Waspaloy. It is postulated that this is due to a high Nb content of the γ’ in alloy 718Plus [23]. This slow aging reaction may be partially responsible for the good processing characteristics of the alloy and for its good response, like alloy 718, to direct age (DA) processing.

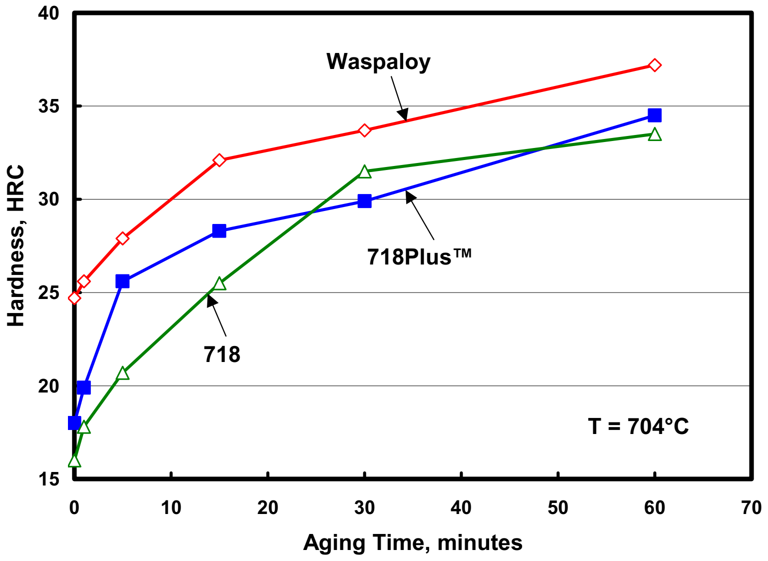


Figure 3. Aging Curves of Alloy 718Plus™ at 704°C vs. Alloys 718 and Waspaloy.

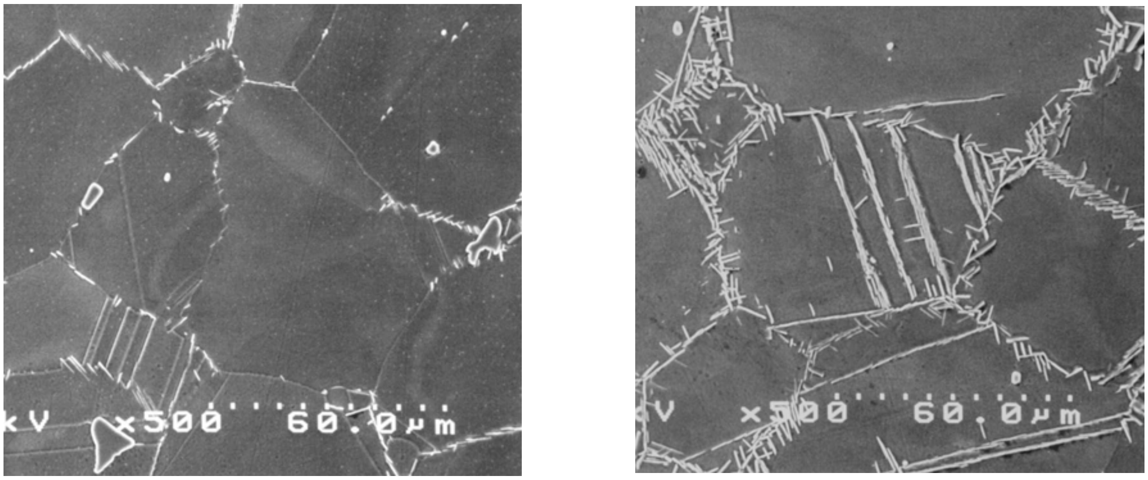
Heat Treatment and Structure

During initial development trials, the standard alloy 718 solution treat and aging (STA) cycle was employed (954°C + 718°C + 621°C). It was subsequently learned that higher aging temperatures were required for optimum properties. Recommended heat treatment for the alloy is now:

954°C-982°C-1 Hr-Rapid Cool + 788°C-2-8 Hrs-FC @ 56°C/min. + 649°C-704°C-8 Hrs-AC

A “pre-solution” treatment, consisting of heating in the temperature range of 816°C to 871°C for about eight hours, has also been employed with the alloy. The purpose of this treatment was to assure the presence of a small amount of δ phase in the grain boundaries.

Like most superalloys there is a strong relationship between processing, structure and properties for alloy 718Plus. Optimum mechanical properties are achieved with a microstructure which has a small amount of rod shaped δ particles on the grain boundaries like that shown in Figure 4(a). Excessively high forging temperatures or high solution heat treating temperatures will result in structures with little or no δ phase precipitates that are prone to notch stress rupture failure. No notch problems have been experienced using the 954°C solution temperature, probably because some δ phase can be precipitated at this temperature. However, excessively long heating times and possibly large amounts of stored, strain energy can result in large amounts of δ phase appearing on grain boundaries, twin lines and intragranularly, Figure 4(b). Such structures can lead to lower than expected tensile and rupture strength. There is still much to be learned about these relationships, but it is fully expected that once specific component manufacturing practices are established, good reproducible mechanical properties will result from the same degree of control exercised with other similar alloys.



(a) (b)

Figure 4. SEM Micrographs of Alloy 718Plus™ with (a) Preferred δ Phase Morphology and (b) Excessive δ Phase.

The effect of cooling rate from solution temperature is shown in Figure 5. These results are plotted as the percentage of the rapid cooled mechanical properties versus the inverse of cooling rate. Data from two different grain size products were generated. The slowest cooling rate tested was calculated as being equivalent to air cooling of a 400 mm thick section. Room temperature and elevated temperature yield strength losses for the two different grain size materials were almost identical. The magnitude of the losses was not excessive considering the slow cooling rates employed. Although comparable testing was not done on alloy 718 or Waspaloy, it is believed that alloy 718Plus is probably more sensitive to cooling rate than alloy 718 but less so than Waspaloy.

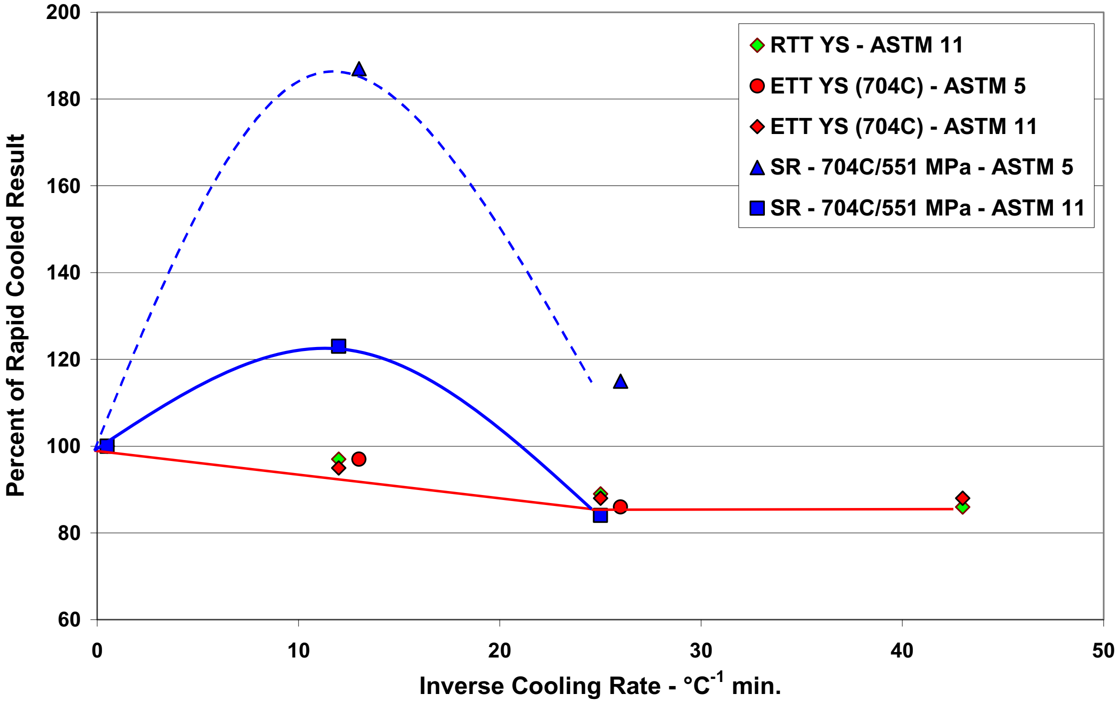


Figure 5. Effect of Cooling Rate from Solution Temperature on Properties of Alloy 718Plus™.

Stress rupture life sensitivity to cooling rate gave a rather surprising result. Life peaked at an intermediate cooling rate, suggesting there may be an optimum cooling rate range, rather than the fastest cool possible for achieving the best combination of tensile and rupture properties for alloy 718Plus. Further work is necessary to fully understand the effects of cooling rate for this alloy.

Mechanical Properties

A substantial amount of mechanical test data has been accumulated to date from Allvac in-house testing, government sponsored programs and various customer evaluations. Results for many of these efforts are reported in these proceedings.

Tensile properties as a function of temperature are presented in Figure 6. Alloys 718 and 718Plus represent Allvac tests of materials with the same grain size. Waspaloy data represents a combination of Allvac production bar data and published data. Yield strength for alloy 718 slightly exceeds that of alloy 718Plus from room temperature through 650°C. At temperatures of 700°C or higher, alloy 718Plus is stronger. It is also substantially stronger than Waspaloy over the entire temperature range tested. Ductilities for all three alloys are quite high, usually above 20% at all test temperatures.

Stress rupture data taken from Allvac forged billet is compared to published data for alloys 718 and Waspaloy in Figure 7. The 718Plus alloy curve corresponds almost exactly to a 55°C increase in temperature capability compared to alloy 718. In the low temperature, high stress test region, 718Plus alloy shows the most significant advantage over Waspaloy. The stress rupture life curves converge in the high temperature, low stress regime but a limited amount of creep testing suggests that steady state creep rates for alloy 718Plus may still be significantly lower than those of Waspaloy.

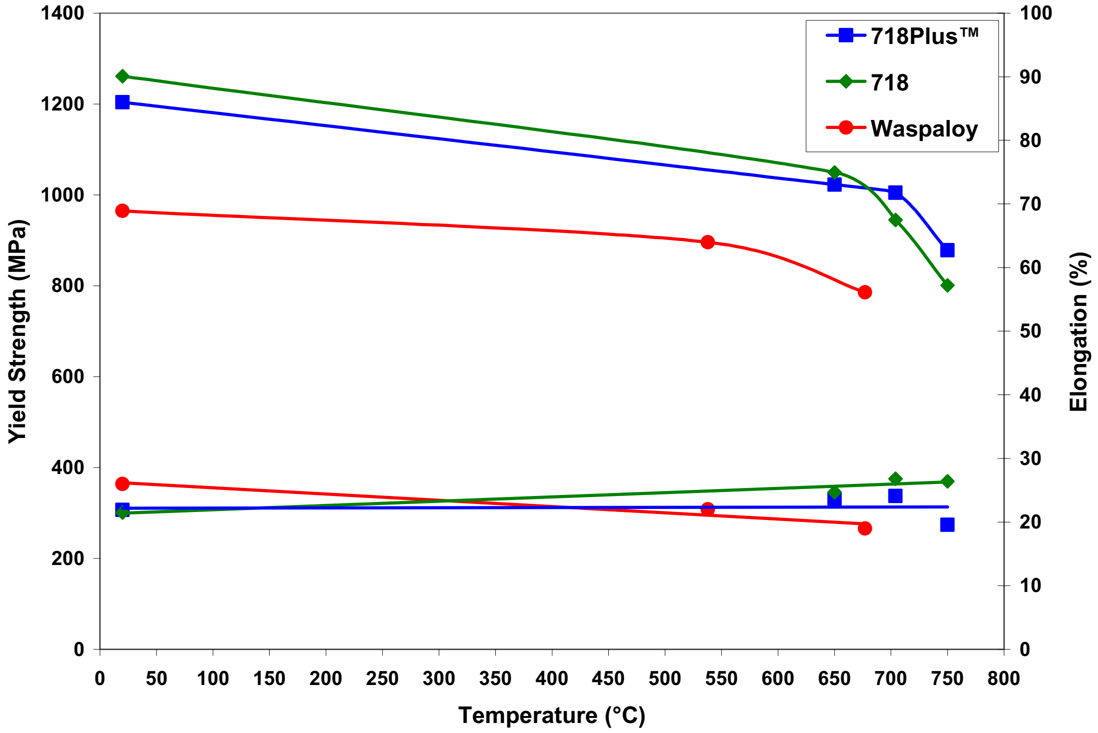


Figure 6. Tensile Yield Strength and Elongation for Alloys 718Plus™, 718 and Waspaloy as a Function of Temperature.

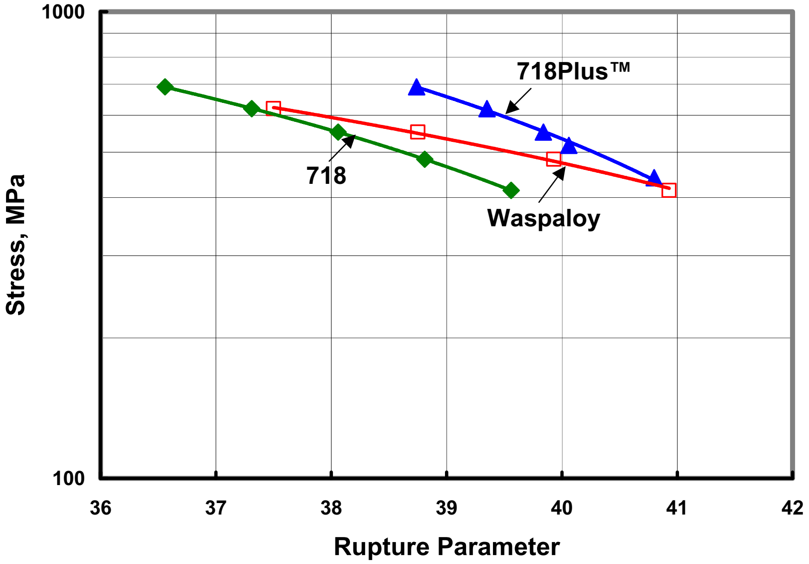


Figure 7. Larson-Miller Plot of Stress Rupture Life of Alloy 718Plus™.

Results from the first study of fatigue crack growth testing of alloy 718Plus were reported in reference [24]. Hold time crack growth rates from that testing are shown in Figure 8. Data for alloy 718Plus was intermediate to Waspaloy, which has the lowest crack growth rate, and alloy 718 which had the highest. However, significant differences in the grain size of the test materials and a lack of comparative properties suggested the need for a more controlled study. The results of this follow-on study will be reported at a future time.

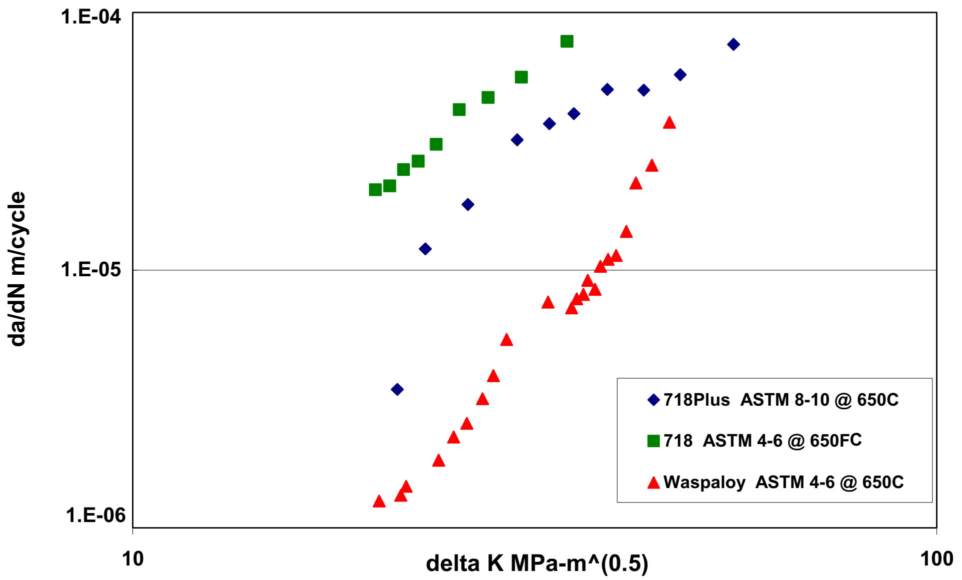


Figure 8. Fatigue Crack Growth With 100 Second Hold Time.

Processing

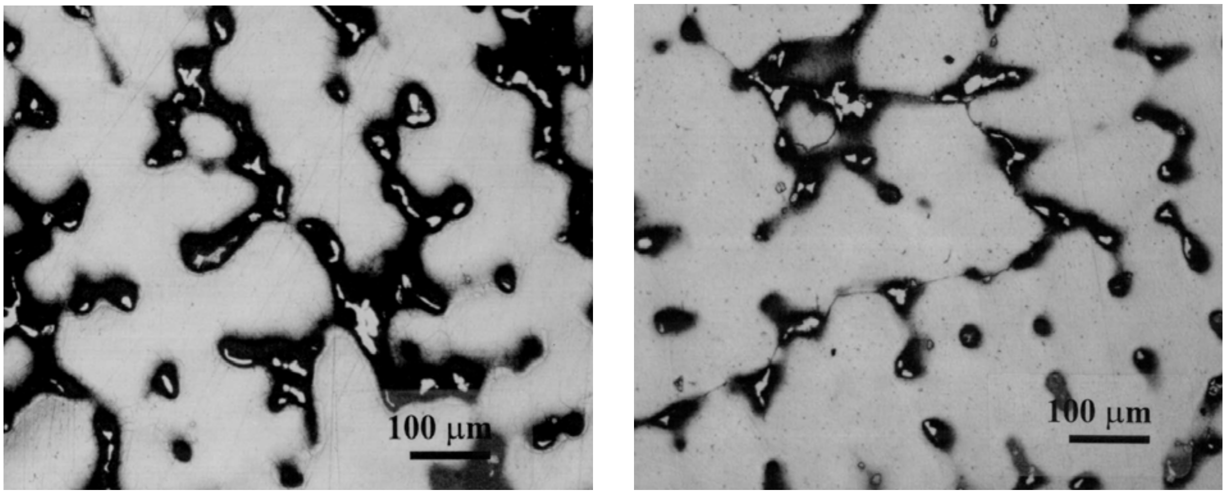
Melting

Process knowledge for alloy 718Plus must still be considered to be at an early stage although it has advanced well beyond the laboratory or experimental phase. Several full scale, production heats have been melted to date and ingots as large as 508 mm x 4500 kg have been successfully produced. Like alloy 718, primary melting has been Vacuum Induction Melting (VIM). Most ingots have been remelted by Vacuum Arc Remelting (VAR) although product has also been produced by triple melting VIM + Electroslag Rapid Remelting (ESR) + VAR.

Melting and remelting practices have been patterned after alloy 718. Figure 9 shows the as-cast structure of the two alloys at the mid-radius location of 508 mm ingots. The two structures are similar but the alloy 718Plus appears to have slightly less Laves phase and associated, dark etching microsegregation. Quantitative measurements have not yet been made. No freckles or white spots have been observed in any of the product made to date. Based on these empirical observations, it is suggested that very large ingots could be produced in alloy 718Plus, similar to the 36” diameter capability for alloy 718, should the need for such large product size arise.

Hot and Cold Working

The hot workability of alloy 718Plus is good. Hot working operations, including ingot breakdown and billet forging, ring rolling, round and rectangular bar rolling and disk forging have all suggested that hot workability is close to that of alloy 718 and much better than Waspaloy. Initial ring rolling trials suggested a 50% reduction in the number of reheats and 6% reduction in conditioning losses compared to Waspaloy. Rapid strain rate hot tensile data confirm these observations. Figure 10 illustrates percent reduction in area as a function of temperature for alloy 718Plus contrasted to the ductility ranges for a large number of heats of alloys 718 and Waspaloy. Clearly hot ductility of alloy 718Plus is intermediate to alloy 718 and Waspaloy. Low values of %RA, which usually correspond to cracking problems in hot working, begin at higher temperatures than for alloy 718 but lower than for Waspaloy.



(a) (b)

Figure 9. Optical Micrographs of Mid-Radius Location, 504 mm Ingot (a) Alloys 718 and (b) 718Plus™.

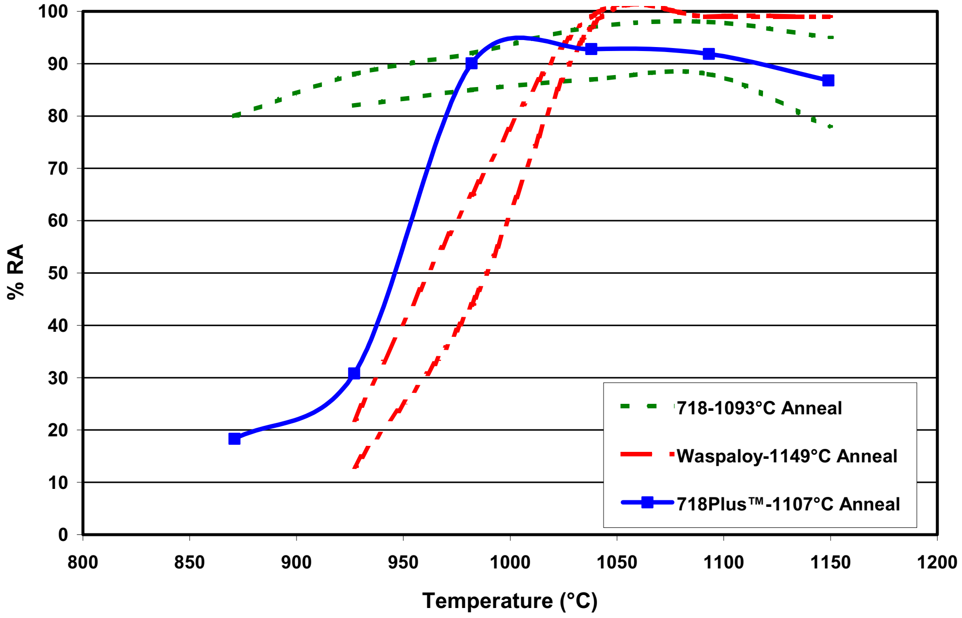


Figure 10. Rapid Strain Rate Hot Tensile Hot Workability Comparison of Alloys 718, Waspaloy and 718Plus™.

Good hot workability, delta phase precipitation and the relatively slow aging response of alloy 718 permit the use of specialized hot working practices to generate special structures and properties. The alloy responds well to warm forging, from furnace temperatures as low as 927°C, and direct aging to achieve a significant boost in tensile strength. Detailed papers on DA processing of alloy 718Plus by Cao, *et al.* [25] and Lemsky, *et al.* [26] are also reported in these proceedings.

The ability to precipitate δ phase and hot work from below the δ solvus temperature opens the door to fine grain processing. Laboratory rolling trials have produced structures with grain sizes as small as ASTM 13.5 (3µm) with a uniform distribution of small δ particles. Such structures would be expected to display a high degree of superplasticity.

Alloy 718Plus can be solution treated and quenched to low hardness levels (≤R_C 20 depending on section thickness), permitting heavy cold working. Both cold drawing of bar [27] and cold working of sheet and strip [28] have been successfully completed using techniques typical of those normally employed for Ni-base alloys.

Welding

Weldability of alloy 718Plus is believed to be quite good, at least intermediate to alloys 718 and Waspaloy. The chemistry of the alloy places it well within the "readily weldable" space relative to post weld heat treat cracking, defined by Haafkens and Mathey [29], as shown in Figure 11.

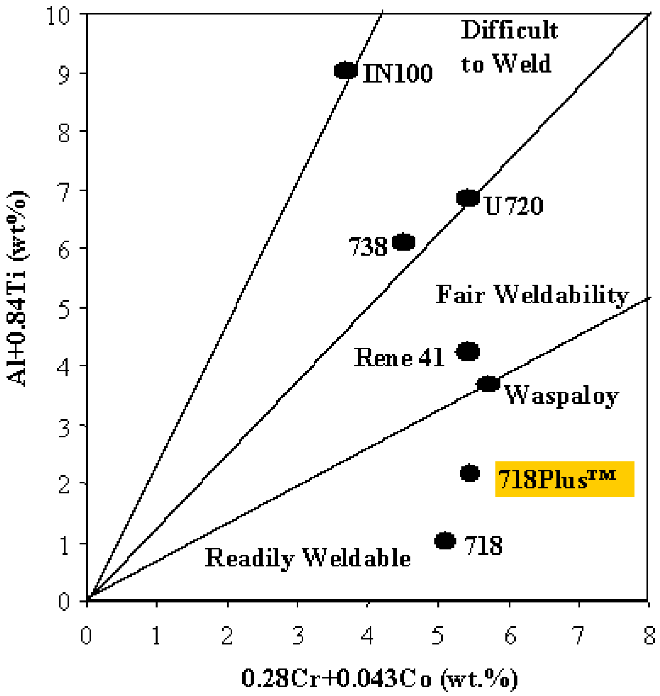


Fig. 11. Effect of Chemistry on Post Weld Heat Treat Cracking.

A mechanical property test developed at Rocketdyne in 1960 [30] termed the Controlled Heating Rate Test (CHRT) relates hot tensile ductility to strain age cracking. The higher the ductility in the temperature range of 816°C to 899°C, the greater the resistance to strain age cracking. Test results from 2.5 mm alloy 718Plus sheet are shown in Figure 12 compared to data published recently by Klarstrom, *et al.* [31]. Result show that alloy 718Plus compares very favorably to good welding alloys 718 and C263 and clearly is much superior to Waspaloy and René 41, both difficult to weld alloys.

Other tests completed to date include fillerless fusion weld bead studies at Allvac, which showed numerous cracks in Waspaloy, but none in alloys 718 or 718Plus. University of Manitoba studies [32] of EB, heat effected zone microfissuring ranked alloy 718Plus intermediate to alloys 718 and Waspaloy, but additional study is underway with samples having a more consistent grain size. Various other unpublished trials by TIG and EB have reported improved weldability compared to Waspaloy. Kloske, *et al.* [33] showed no improvement over Waspaloy in MIG welding of castings, but these results were potentially influenced by an extremely poor quality weld wire. Further studies are required as well as results from actual component welding experience.

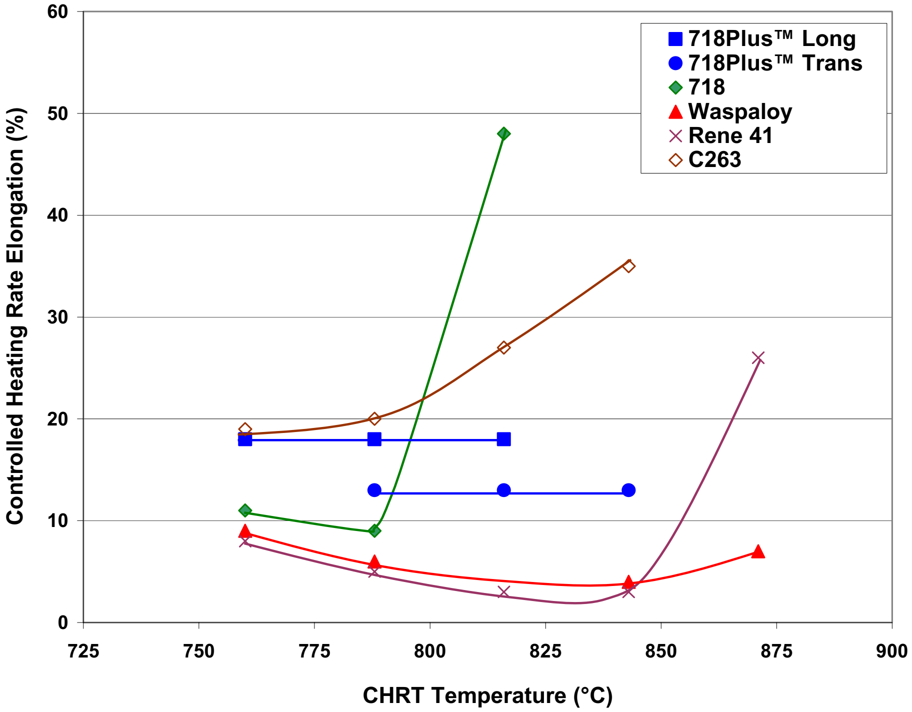


Fig. 12. Weld Strain Age Cracking Ranking via Controlled Heating Rate Test.

Applications and Cost

Interest in alloy 718Plus continues to increase on the part of US and European manufacturers. Evaluations of varying types are underway or planned by all of the jet engine OEM's, land based turbine OEM's, several closed die forgers, ring rollers, flash butt welded ring makers, engine component fabricators and investment casters. Some of this work is supported by government funding but most is proceeding on internal, company R&D funding.

The first commitment to a production use of alloy 718Plus has been made for a high temperature tooling application, replacing Waspaloy as a hot shear knife. The first component test for an aeroengine application is expected to be as a static, fabricated case. Other applications being considered or tested include aero and land-base turbine disks, forged compressor blades, fasteners, engine shafts and fabricated sheet/plate components. Product forms include rolled or flash butt welded rings, closed die forgings, bar, rod, wire, sheet, plate and castings.

Cost is obviously a major consideration in the selection of a new alloy. The cost of finished components of alloy 718Plus is expected to be intermediate to alloys 718 and Waspaloy. This is driven first by the intrinsic raw material content of the alloys. Raw material costs for alloys 718, Waspaloy and 718Plus were calculated based on the most recent five year averages for Ni, Co, Mo and FeNb and the results, ratioed to Waspaloy, are summarized in Table V. These elements make up the major cost differentiations for the three alloys in question.

Table V. Relative Raw Material Cost of Alloys (Five Year Average)

Alloy 718	Waspaloy	Alloy 718Plus™
69	100	92

Alloy 718Plus calculates at eight percent less costly than Waspaloy. Specific point-in-time calculations will vary from this value depending on the raw material spot prices. Further cost savings over Waspaloy parts are expected because of the better workability of alloy 718Plus.

Fewer process steps and higher yield in mill processing of bar, billet and forgings and better buy to fly ratios should be possible. Although difficult to quantify, lower life cycle costs might also result from better properties and improved weldability (repair welding).

Revert is another factor which enters prominently in cost of Ni-superalloy mill product. There is a well established revert cycle in the superalloy industry which returns a large amount of the manufacturing scrap back into the melting cycle, usually with an associated cost savings. The ability to use revert is an important consideration in the cost of a new alloy. Alloy 718Plus is an excellent scrap consumer because it contains both Fe and Co. Heats can be formulated using large amounts of scrap of the most common Ni-base alloys, including 718, Waspaloy, 625, René 41 and lesser amounts of several others. Mixed scrap, containing both Fe and Co, which would be unusable in either 718 or Waspaloy, may be usable in 718Plus preventing the loss of such material to other scrap cycles.

Conclusions

Allvac has introduced a new, precipitation hardening, Ni-Cr-Co-Fe base superalloy, Allvac® 718Plus™, which has achieved the long standing desire for a moderately priced alloy with a significant improvement in temperature capability, while retaining many of the desirable characteristics of alloy 718. The following conclusions suggest the alloy will have a long and successful life like alloy 718.

- Development of alloy 718Plus has advanced to the level of full scale production with good results. Multiple ingots of typical production scale 718Plus alloy have been melted and converted to product. Numerous evaluation programs are ongoing with OEM's, forgers, fabricators and government agencies.

- Much has been discovered about the metallurgy and processing of alloy 718Plus. The alloy has many similarities to alloy 718, but much remains to be learned to achieve the full potential of the alloy.

- Alloy 718Plus has a comparable tensile strength with a 55°C temperature advantage over alloy 718. It has higher tensile and creep strength than Waspaloy and comparable thermal stability up to at least 704°C. Because of its good process and metallurgical flexibility, alloy 718Plus, like alloy 718, opens opportunities for special processing such as fine grain and mini-grain, superplastic forming, direct age forging, casting and large ingot capability.

- Alloy 718Plus enjoys an intrinsic raw material cost advantage over Waspaloy. Additional cost savings are expected because of the alloy's improved fabricability.

- Alloy 718Plus will not replace alloy 718 or Waspaloy, but it fits perfectly into the gap created by the temperature limitation and the cost and processing difficulties of these two most widely used superalloys. Alloy 718Plus will find numerous applications as components currently manufactured from both of these two alloys.

Acknowledgements

The author would like to acknowledge the inventor of Allvac® 718Plus™, Dr. Wei-Di Cao, and recognize his relentless pursuit of an improved alloy 718 over many years. Special thanks also go to ATI Allvac management for supporting this work through a time period when such activities have generally fallen from business favor.

1. R.E. Shafrik, D.D. Ward, J.R. Groh, *Superalloys 718, 625, 706 and Various Derivatives*, ed. E.A. Loria, TMS, June 2001, 1-11.

2. D.F. Paulonis, J.J. Schirra, *Superalloys 718, 625, 706 and Various Derivatives*, ed. E.A. Loria, TMS, June 2001, 13-23.

3. 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.

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

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

6. 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.

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

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

9. 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.

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

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

12. R.L. Kennedy, W.D. Cao, T.D. Bayha and R. Jeniski, *Niobium for High Temperature Applications*, ed. by Young-Won Kim and Tadeu Carneiro, TMS, 2004, pp. 11-21.

13. W.D. Cao and R.L. Kennedy, *Superalloys 2004*, Seven Springs Conference, Seven Springs, PA, TMS, 2004, pp. 91-99.

14. W.D. Cao and R.L. Kennedy, *Acta Metallurgica Sinica*, Vol. 18, No. 1, February 2005, pp 39-46.

15. W. D. Cao and R.L. Kennedy, Superalloys 718, 625, 706 and Various Derivatives, ed. by E.A. Loria, TMS, 2001, 463-477.

16. M. K. Miller, J. A. Horton, W. D. Cao and R. L. Kennedy, *Journal De Physique IV*, *Colloque C5*, *supplement au Journal de Physique III*, Volume 6, September, 1996, 589-599.

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

---

18. C. G. McKamey, C. A. Carmichael, W. D. Cao, R. L. Kennedy, *Scripta Materialia*, Vol. 38, No. 3, 1998, 485-491.

19. W.D. Cao and R.L. Kennedy, Superalloys 2000, ed. T.M. Pollock, *et al.*, TMS, 2000, 101-108.

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

21. W. D. Cao and R.L. Kennedy, Superalloys 718, 625, 706 and Various Derivatives, ed. E.A. Loria, TMS, 2001, 455-464.

22 . X. Xie, G. Wang, J. Dong, C. Xu, W.D. Cao and R.L. Kennedy, *Superalloys 718, 625, 706 and Various Derivatives*, ed. E.A. Loria, TMS, 2005.

23. W.D Cao, *Superalloys 718, 625, 706 and Various Derivatives*, ed. E.A. Loria, TMS, 2005.

24. X. Liu, S. Rangararan, E. Barbero, K.M. Chang, W.D. Cao, R.L. Kennedy and T. Carneiro, *Superalloys 2004*, The Seven Springs Conference, Seven Springs, PA, TMS, 2004, pp. 283-290.

25. W.D. Cao and R.L. Kennedy, *Superalloys 718, 625, 706 and Various Derivatives*, ed. E.A. Loria , TMS, 2005.

26. J. Lemsky, K. Kloske, T.D. Bayha, H. Siczek, *Superalloys 718, 625, 706 and Various Derivatives*, ed. E.A. Loria ,TMS, 2005.

27. B.J. Bond and R.L. Kennedy, *Superalloys 718, 625, 706 and Various Derivatives*, ed. E.A. Loria, TMS, 2005.

28. D. Bergstrom and T.D. Bayha, *Superalloys 718, 625, 706 and Various Derivatives*, ed. E.A. Loria, TMS, 2005.

29. M.H. Haafkens and J.H. Matthey, *Welding Journal*, November 1992, p. 25-30.

30. R.W. Fawley and M. Pragen, *WRC Bulletin 150*, Welding Research Council, NY, 1970.

31. D.L. Klarstrom, V.R. Ishwar and M.D. Rowe, *Acta Metallurgica Sinica*, Vol. 18, No. 1, February 2005, 1-14.

32. K.R. Vishwakarma, N.L. Richards and M.C. Chaturvedi, *Superalloys 718, 625, 706 and Various Derivatives*, ed. E.A. Loria, TMS, 2005.

33. K. Kloske, M. Liu and T.D. Bayha, *Superalloys 718, 625, 706 and Various Derivatives*, ed. E.A. Loria, TMS, 2005.