

# Development of ATI Allvac<sup>®</sup> 718Plus<sup>®</sup> Alloy and Applications

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**Keywords:** Allvac<sup>®</sup> 718Plus<sup>®</sup> Alloy, Alloy 718, Waspaloy, René 41, Superalloys, Cost, Applications, Processing, Mechanical Properties.

## Abstract

ATI Allvac has developed a precipitation hardened nickel-based superalloy, Allvac<sup>®</sup> 718Plus<sup>®</sup> Alloy, capable of maintaining excellent strength and stress-rupture properties to 704°C (1300°F). The alloy is designed to have the temperature capability and thermal stability of Waspaloy while retaining the processing characteristics of standard alloy 718.

Allvac 718Plus alloy has a cost advantage over Waspaloy due to lower intrinsic raw material costs and improved hot workability and weldability that leads to better material yields in finished components. These desirable characteristics are prompting turbine engine manufacturers to choose 718Plus alloy for both rotating and non-rotating components in their next generation designs or to replace incumbent alloys like Waspaloy and René 41 in legacy engines.

This paper will review the development of Allvac 718Plus alloy and provide comparisons of the chemistry and mechanical properties with other nickel-based superalloys. The product forms and current production status of the alloy will be reviewed along with a detailed look at specific applications.

## Introduction

Alloy 718, patented in 1964 by Inco [1], is today's superalloy of choice for a wide variety of turbine engine applications including both rotating and static components. Alloy 718 is available in many product forms (e.g. forgings, castings, sheet) and by volume makes up 55-70% of the nickel-based superalloys used in modern jet engines [2,3]. The reason for the success of alloy 718 lies with its combination of good strength, weldability, castability, workability, and moderate cost [2,3]. Despite its widespread use in turbine engines, alloy 718 becomes limited in its application once exposure temperatures enter the range of 565°C–650°C (1050°F–1200°F).

The ability of 718 to be used in this critical temperature range is dependent on time, stress, critical design parameter (strength, stress-rupture, fatigue crack growth rate, etc.), safety factor, and other factors that each OEM will view and value differently. Once an

application's requirements surpass the capability of alloy 718, the cost for that component can go up significantly as alloys with greater temperature capability than 718 contain more expensive raw materials (e.g. cobalt and molybdenum) and are more difficult to process. René 41 and Waspaloy, developed in the 1950's and 40's by GE and Pratt & Whitney, respectively, are two alloys commonly used in applications requiring good strength at temperatures greater than 650°C (1200°F). These alloys have higher raw material costs from increased amounts of nickel, cobalt and molybdenum and are more difficult to fabricate than alloy 718 making them significantly more expensive. Turbine engine manufacturers and superalloy producers have long desired an alloy with the strength and stress-rupture capabilities of alloy 718 where the use temperature could be extended up to 704°C (1300°F) without loss of weldability or formability and a minimal cost penalty.

### Development of 718Plus Alloy

**Chemistry.** Initial studies at ATI Allvac to develop an alloy with a higher temperature capability than alloy 718 began in the early 90's with the baseline composition of alloy 718 but used increased phosphorous and boron levels [4]. The result of these studies was Allvac<sup>®</sup> 718ER<sup>®</sup> Alloy which provided the equivalent stress-rupture life of standard 718 at a test temperature of 11-16°C (20-30°F) higher than the 650°C (1200°F) standard test temperature [4]. Since the primary strengthening precipitate of 718ER alloy remained  $\gamma''$ , a phase with poor thermal stability above 650°C, the improvement in stress-rupture temperature capability was limited and long time thermal stability was unaffected. Studies began in 1997 to create a new alloy with higher temperature capability and better thermal stability. Alloy 718Plus was born with the following attributes [5]:

- A 55°C (100°F) temperature advantage in stress-rupture performance over alloy 718
- Improved thermal stability, equal to Waspaloy at 704°C (1300°F)
- Good weldability, similar to alloy 718 and better than Waspaloy
- Good workability, similar to alloy 718 and better than Waspaloy

In the development of 718Plus alloy, extensive pilot plant work was conducted on small heats along with modeling studies. Cao observed that a 4:1 Al/Ti ratio in atomic percent and 4 atomic percent of Al+Ti provided the optimal combination of good high temperature strength and thermal stability [6,7]. Thermal stability, stress rupture, and tensile strength were also optimized with 9% cobalt, 10% iron, a tungsten addition of 1% along with the same molybdenum and niobium levels found in standard alloy 718. The end result of Cao's work is the chemistry of 718Plus alloy shown in Table 1.

Alloy	Chemistry											
	C	Ni	Cr	Mo	W	Co	Fe	Nb	Ti	Al	P	B
718	0.025	B	18	2.8	----	----	18	5.4	1	0.5	0.006	0.004
718Plus Alloy	0.020	B	18	2.8	1	9	10	5.4	0.7	1.5	0.006	0.004
Waspaloy	0.035	B	19.4	4.3	----	13.3	2 max	----	3	1.3	0.006	0.006
René 41	0.040	B	19	10	----	11	5 max	----	3.1	1.5	0.006	0.006

Table 1. Nominal Chemistry of Alloy 718, Allvac<sup>®</sup> 718Plus<sup>®</sup> Alloy, Waspaloy and René 41

**Precipitating Phases.** The precipitation phases found in 718Plus alloy have been studied by Kennedy [8], Cao [9], and Xie [10,11]. The primary strengthening phase is  $\gamma'$  with a volume fraction ranging from 19.7-23.2 %, depending on the quantity of  $\delta$  phase [9]. Gamma prime strengthened alloys like Waspaloy and René 41 have much greater stability at higher temperature than  $\gamma''$  strengthened alloys like 718 since  $\gamma''$  grows rapidly and partially

decomposes to equilibrium  $\delta$  phase at temperatures in the 650–760°C (1200–1400°F) range [9]. Studies of the  $\gamma'$  phase in 718Plus alloy show it to be high in Nb and Al, which is very different from the  $\gamma'$  present in Waspaloy and René 41 [9], and may account for its unique precipitation behavior and strengthening effects. Alloy 718Plus does contain  $\delta$  phase which is beneficial for conferring stress rupture notch ductility and controlling microstructure during thermomechanical processing. However, the volume fraction of the delta phase is considerably less than is found in alloy 718 and tends to be more stable with a much slower growth rate at elevated temperatures. Some  $\gamma''$  may also be present in 718Plus alloy but in a much lower quantity, less than 7%. Figures 1a and b show the precipitates in alloy 718 and 718Plus alloy, respectively, after 500 hours of exposure to 760°C (1400°F).

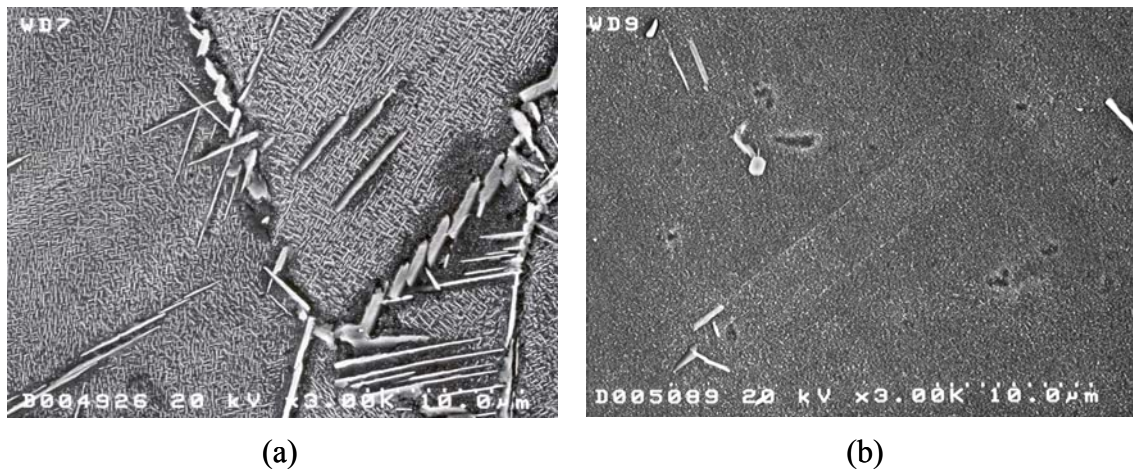


Figure 1. SEM micrographs of Alloy 718 (a) and 718Plus<sup>®</sup> Alloy (b) after 500 hours of exposure to 760°C (1400°F).

**Processing.** From the perspective of ingot and billet processing, the production of 718Plus alloy mimics that of alloy 718. The hot workability of 718Plus alloy and Waspaloy is illustrated in Figure 2. These data show the reduction in area as a function of test temperature for high strain rate tensile tests. These results confirm an improvement in the minimum hot working temperature for 718Plus alloy of approximately 55°C over Waspaloy.

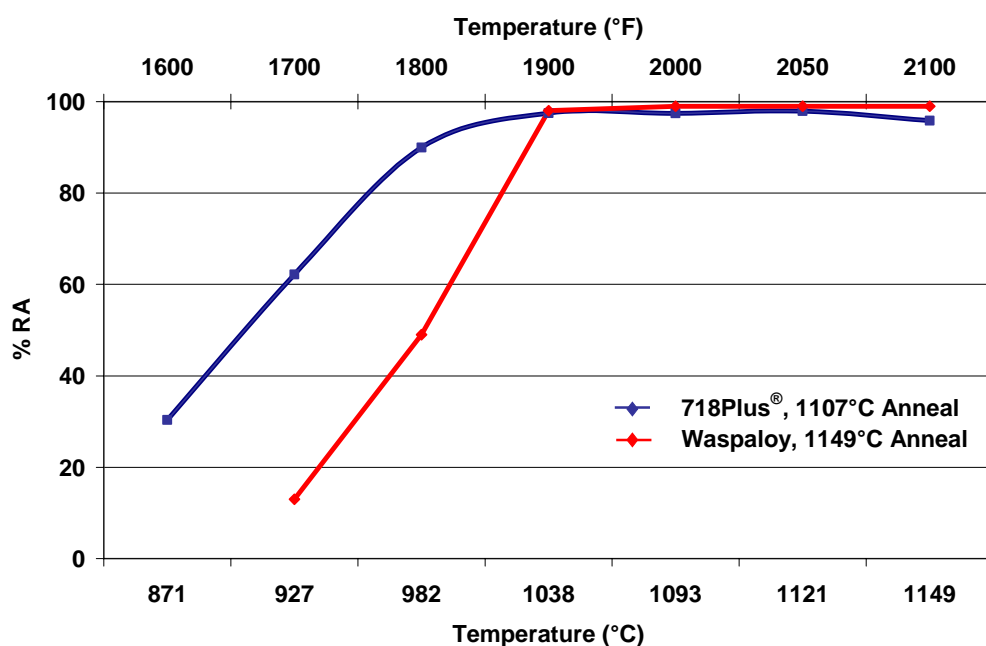


Figure 2. Reduction in Area as a function of test temperature for 718Plus<sup>®</sup> alloy and Waspaloy. Data is an average of multiple heats for both alloys.

Microstructural response of 718Plus alloy to forging and rolling is very similar to alloy 718. Billet processed using fine-grained forging practices results in average grain sizes of ASTM 7-8, similar to alloy 718. Processing of 718Plus alloy at both ring rolling manufacturers and closed-die forgers has shown the alloy to have substantially better forgeability than Waspaloy and René 41. While it cannot be forged as cold as standard 718, the larger hot-working window for 718Plus alloy allows for a significant reduction in the number of reheats [12,13] compared to Waspaloy or René 41, in addition to less conditioning to remove surface cracking.

**Heat Treatment.** As with other superalloys, the mechanical properties of 718Plus alloy are a function of microstructure which is strongly influenced by thermomechanical processing. The interaction between starting hot working, microstructure and appropriate solution heat treatment practice has been presented in detail by Cao and Kennedy [14]. The proper volume fraction, size, and distribution of  $\delta$  phase are important for obtaining optimal mechanical properties after heat treatment. The ideal as-worked structure should contain a small amount of  $\delta$  phase on the grain boundaries [14]. Materials that are finish hot worked below the delta solvus temperature of approximately 1000°C (1830°F), for example in the range of 927°C-982°C (1700°F-800°F), will usually contain the proper distribution of  $\delta$  phase. For these materials the suggested solution heat treat is 954°C-982°C (1750°F-800°F) for 1 hour followed by air cool or faster. Aging is done with a two-step treatment as is the case with standard alloy 718. The recommended first step age is at 788°C (1450°F) for 8 hours followed by a second step age at 704°C (1300°F) for 8 hours.

Super-solvus forging completed in the temperature range 1010°C-1093°C (1850°F-2000°F) will result in a microstructure that is relatively free of  $\delta$  phase. In this case a pre-solution heat treat soak is recommended. This treatment involves heating the forging to 843°C-871°C (1550°F-600°F) for 8 to 16 hours to precipitate out  $\delta$  phase prior to solution heat treatment, and results in the elimination of notch sensitivity and increased strength [14].

**Properties.** The fabricability of 718Plus alloy in conjunction with the resulting mechanical properties make it unique and of interest to the turbine OEMs. The minimum acceptable properties for 718Plus alloy billet, bar and forgings have been established and submitted as a proposal for an AMS specification (Table 2).

<b>Tensile Test Condition</b>	<b>UTS (MPa)</b>	<b>TYS (MPa)</b>	<b>Elong %</b>	<b>% RA</b>
Room Temperature	1338	958	15	15
704°C (1300°F)	1014	807	13	15

<b>Stress Rupture Test Condition</b>	<b>Time (hrs)</b>	<b>% RA</b>		
704°C (1300°F) at 620 MPa (90 ksi)	39	8		

Table 2. Minimum Tensile and Stress Rupture Requirements for Allvac<sup>®</sup> 718Plus<sup>®</sup> Alloy in AMS Specification Proposal

It is difficult to make comparisons between the AMS specifications for alloys 718Plus, 718 (AMS 5662) and Waspaloy (AMS 5706) due to the different conditions that are specified (e.g. test temperature and rupture stress). Figures 3 and 4 provide some insight into the benefits of 718Plus alloy. Figure 3 shows the fraction of room temperature yield strength that is retained with increasing tensile test temperature for a variety of superalloys. This figure illustrates the ability of 718Plus alloy to maintain strength at higher temperatures compared with alloy 718, in addition to maintaining a strength advantage over Waspaloy up to a test temperature of 760°C (1400°F).

The superior tensile strength of 718Plus alloy over 718 and Waspaloy after long time exposure at 760°C is further illustrated in Figure 4.

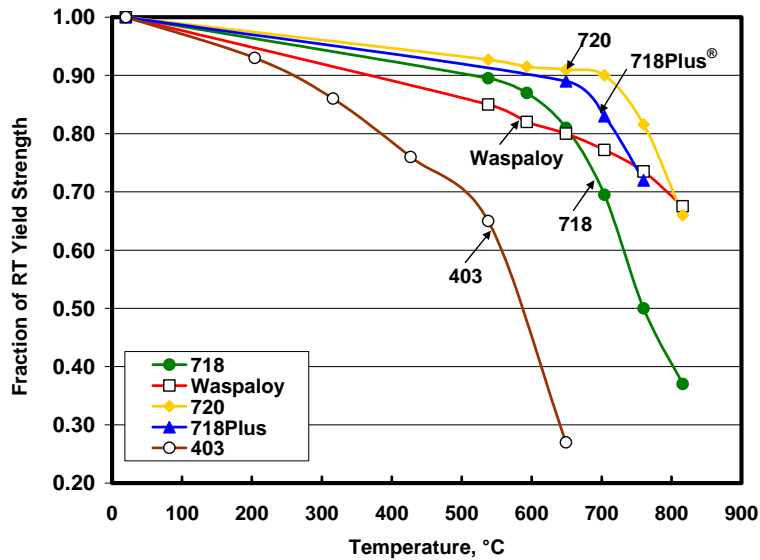


Figure 3. The effect of temperature on the tensile yield strength of selected nickel-based alloys.

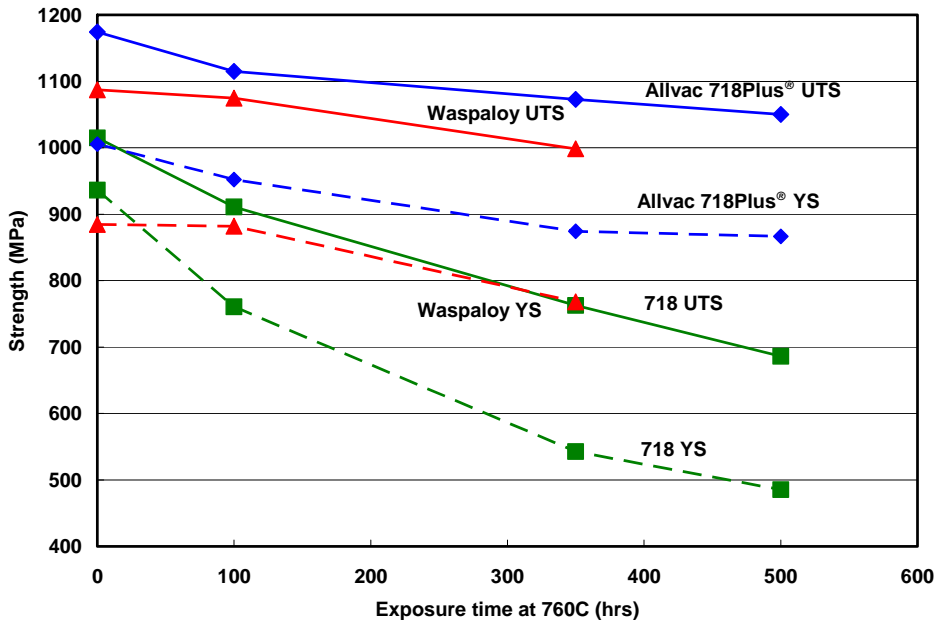


Figure 4. The effect of exposure to 760°C (1400°F) on the tensile properties at 650°C (1300°F).

The stress rupture life of 718Plus alloy shows a substantial benefit over alloy 718 and an advantage over Waspaloy within certain combinations of stress and temperature. The Larson-Miller plot for these three alloys, shown in Figure 5, illustrates the benefits of 718Plus alloy, particularly in the lower temperature-higher stress regime. The results for 718Plus alloy fit almost exactly the curve for alloy 718 shifted up by 55°C (100°F).

Fatigue performance is an area that requires further study, but preliminary data suggests that the dwell-fatigue crack growth performance of 718Plus alloy will be superior to that of standard alloy 718 but perhaps not as good as Waspaloy. Figure 6 shows the fatigue crack growth (FCG) resistance of 718Plus alloy vs. alloys 718 and Waspaloy with a dwell time of 100 seconds. Work is in progress to develop an understanding of the effects of microstructure and environment on FCG. In the absence of a dwell, 718Plus alloy has been shown to have superior fatigue crack growth resistance to both 718 and Waspaloy [15,16].

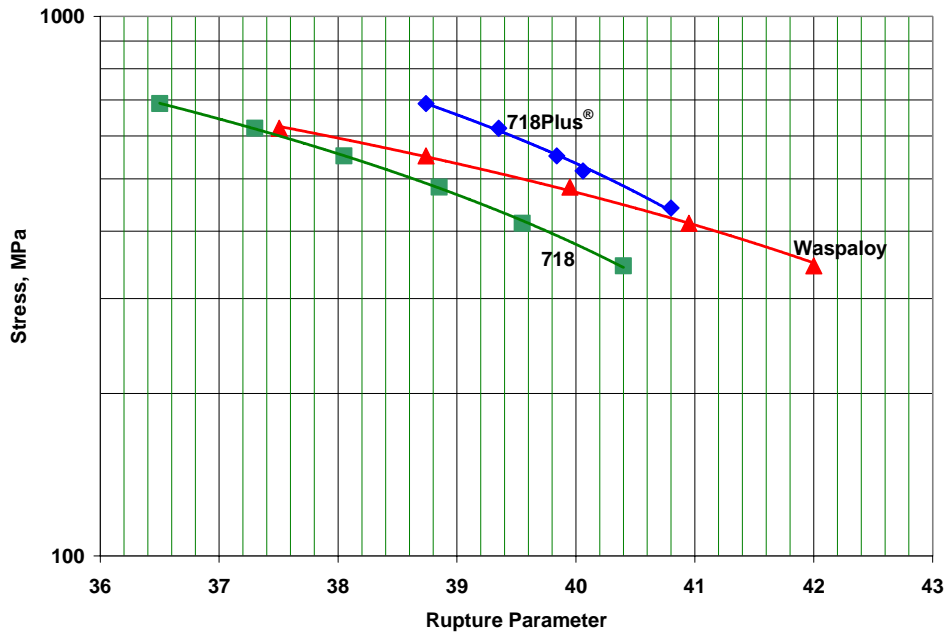


Figure 5. Larson-Miller plot of stress-rupture life of Allvac<sup>®</sup> 718Plus<sup>®</sup> Alloy in comparison with alloys 718 and Waspaloy.

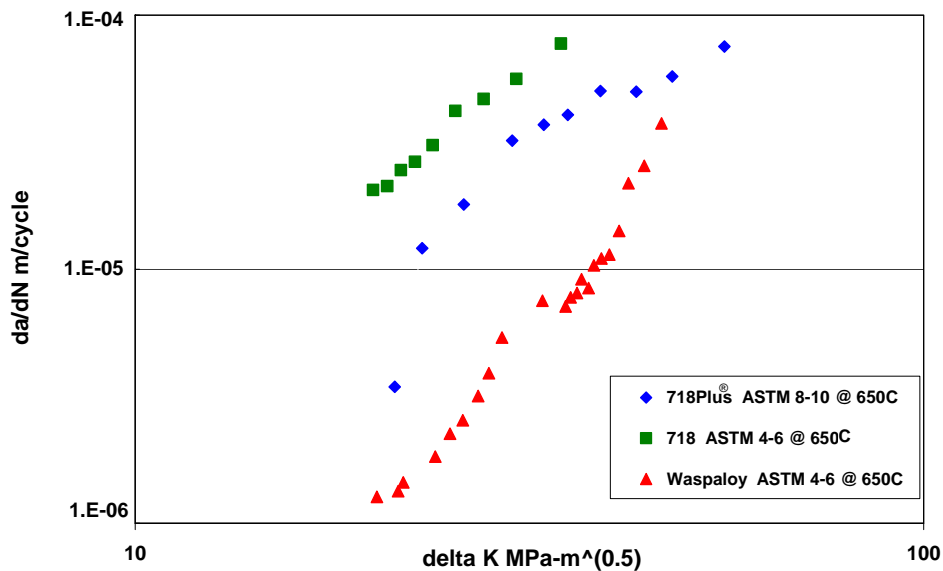


Figure 6. Fatigue crack propagation behavior of alloys Allvac<sup>®</sup> 718Plus<sup>®</sup>, 718, and Waspaloy with 100s hold time.

Improved weldability over Waspaloy is one of the primary drivers for 718Plus alloy in engine applications. The weldability of 718Plus alloy has been reviewed [12] and has been shown to be better than Waspaloy and similar to alloy 718. Figure 7 shows the weld cracking tendency for a number of well known commercial alloys and illustrates the good welding characteristics expected with 718Plus alloy based on its chemistry.

### Product Forms and Commercialization Status

At the time of this publication, Allvac has produced 11 production size VIM heats of 718Plus alloy and shipped more than 21,000 kgs of product. Product sizes range from 1 mm diameter weld wire to 305 mm billet produced from 508 mm ingot. The majority of product has been made from standard VIM plus VAR ingot. Two heats of triple melt (VIM-ESR-VAR) 718Plus alloy were produced and are being evaluated for disc applications. Two heats of VIM-ESR have also been produced and used in the production of flat products.

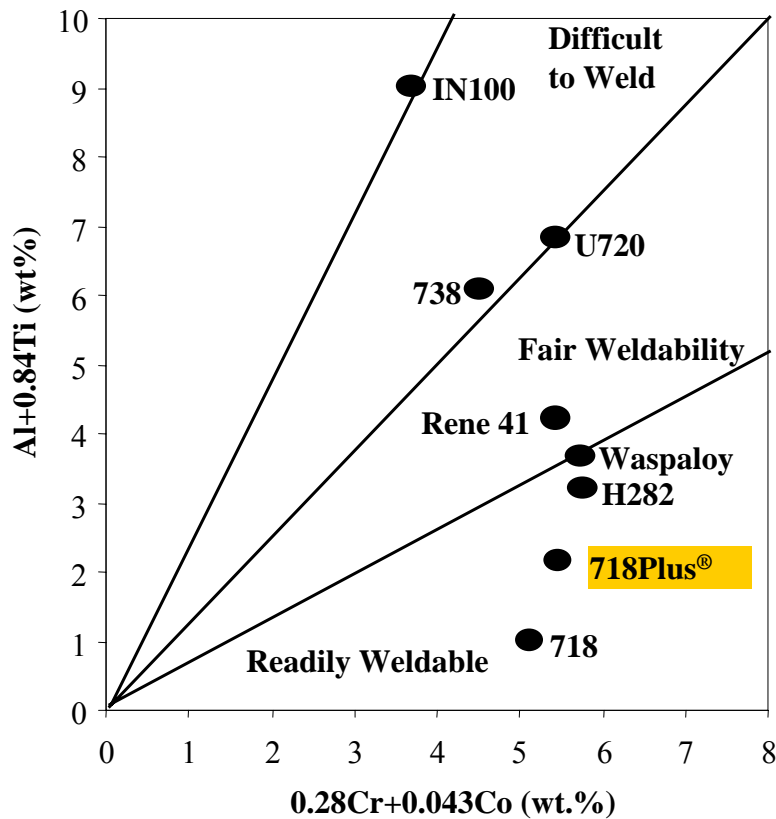


Figure 7. Effect of chemistry on post-weld heat cracking.

Alloy 718Plus is also being developed in flat product forms including plate, sheet, strip, and foil. ATI Allegheny Ludlum has produced 111 mm, 25 mm, and 12 mm plate with full characterization in process. Sheet has been produced and reported on by Bayha and Bergstrom [17]. They confirmed the ability of the alloy to be produced as hot and cold-rolled sheet with the resulting product having good room temperature and elevated temperature properties. As a result of this initial work, ATI Allegheny Ludlum is producing cold-rolled sheet for customer evaluations of varying gauges ranging from 1 mm – 2.5 mm. Some of the cold rolled sheet will be further processed to several foil thicknesses (0.05 mm – 0.18 mm) and evaluated.

Alloy 718Plus is also being considered in investment casting form to replace more expensive casting alloys like Weldable Waspaloy and René 220. Bayha, Lu, and Kloske [18] have reported on the initial results of a casting program and showed that the alloy has similar castability to Weldable Waspaloy with good mechanical properties. A follow-on study to optimize the chemistry for investment casting and produce some full-size parts for evaluation is being funded by the Metals Affordability Initiative (MAI). The team for this program will consist of Allvac, General Electric, Honeywell, PCC Structural Castings, and Rolls-Royce.

To facilitate the acceptance and implementation of 718Plus alloy, ATI Allvac has taken several steps to standardize the alloy. UNS designation N07818 has been assigned. An alloy data sheet is available and posted on [www.allvac.com](http://www.allvac.com). ATI Allvac has created an internal specification that provides customers with a standard to order against in the absence of an OEM specification or industry standard specification. Three AMS specifications covering bar, forgings, rings and weld wire have been applied for and are expected to issue in the fourth quarter of 2006.

## Jet Engine and Power Turbine Applications

**Non-Rotating Applications.** The majority of work performed on 718Plus alloy to this point has been focused on evaluating the alloy for static structural components such as cases and rings. The alloy was down-selected over several competing alloys in a Metals Affordability Initiative program that began in 2001 and was completed in 2005 [12]. The goal of this program was to find a material that could provide a substantial cost savings over incumbent alloys like Waspaloy and René 41 while at the same time providing a 55°C temperature advantage over alloy 718. The results of the program showed that 718Plus alloy met all of the program goals. Full-size component forgings shown in Figure 8 were produced as a part of this effort and repeatedly demonstrated the improved forgeability and lower sensitivity to surface cracking compared to Waspaloy [13,14]. Actual part applications could include turbine and combustor cases, turbine seals and shroud retainer rings.



Figure 8. Full-size component ring-rolled forgings of Allvac<sup>®</sup> 718Plus<sup>®</sup> Alloy produced in the MAI Low Cost High Temperature Structural Material program [12].

The alloy is also being evaluated for flash-butt welded ring applications. Structural castings of interest include diffuser cases, tangential out board injectors, turbine exhaust cases and compressor stators, [18,20]. Sheet is being considered for fabricated engine parts such as turbine exhaust cases and engine seals. Fasteners remain another potential application for 718Plus alloy. Preliminary evaluation of the effects of cold work on the properties has shown good cold workability and tensile yield strengths up to 1305 MPa at 704°C [21].

**Rotating Applications.** The property advantages for 718Plus alloy have also led to its being considered for rotating parts. There has been a substantial amount of work published on forged pancakes as the first step in evaluating the alloy for turbine disc applications [22,23, 24]. Figure 9 shows 75 mm tall by 225 mm wide subscale disc forgings produced by Wyman Gordon and 50 mm tall by 500 mm wide pancake forgings by the Ladish Company.



Figure 9. (a) Sub-scale disc forgings produced by Wyman Gordon Houston. (b) Pancake forgings produced by the Ladish Company.

Cao and Kennedy have shown that 718Plus alloy is capable of direct aging (DA), low temperature working followed by aging with no prior solution heat treatment [25]. DA processing resulted in the production of very fine grain material with yield strength improvement at 704°C of 70-100 MPa. Further study is needed to optimize the process and fully evaluate the impact on creep-rupture and fatigue crack growth. The alloy is also being considered for blading applications in areas where alloy 718 is limited due to elevated operating temperatures.

### **Applications in Non-Turbine Engine Components**

Alloy 718Plus is also finding applications outside of the jet engine and power turbine OEMS. Tooling applications hold particular promise due to the alloy's good fabricability, temperature capability improvement over alloy 718, and cost benefit over Waspaloy and other higher temperature alloys. The alloy is currently used for shear knife applications across all Allegheny Technology companies replacing Waspaloy. It is also being tested for open die forging tools and extrusion tooling.

Any application that currently uses alloys 718, Waspaloy, René 41 or other nickel-based superalloys can consider 718Plus alloy as a substitute for reasons of cost savings or increased temperature capability. Other markets where 718Plus alloy has potential are automotive turbochargers or industrial markets like chemical process or oil and gas where alloy 718 is used.

### **Implementation of 718Plus Alloy**

Due to the extensive characterization and testing requirements required prior to implementing an alloy into a turbine engine, 718Plus alloy has not yet been put into service in a turbine engine. The first engine test of the alloy is anticipated in early 2007 with standard production part introduction later in 2007/2008. First implementation of the alloy is likely to be for non-rotating parts such as rings and cases due to the lower risk involved and lesser amount of testing required.

Alloy 718Plus is currently being evaluated by thirteen OEMs for a variety of applications. Another thirteen parts manufacturers have made parts such as rolled rings, open-die pancake and closed die forgings. Since it was officially introduced in 2003, the alloy has spurred a great deal of interest and activity that will lead to rapid implementation relative to previous superalloys. This is due at least in part to the longstanding demand for an alloy of moderate cost than can be used in operating environments at 704°C (1300°F).

### **Summary**

ATI Allvac has developed a precipitation hardened nickel-based superalloy, Allvac<sup>®</sup> 718Plus<sup>®</sup>, that has 704°C (1300°F) temperature capability with enhanced fabricability. The unique combination of good elevated temperature strength, thermal stability, hot workability, and weldability, at a lower cost than Waspaloy, are leading to implementation in many types of turbine engine applications. Over 26 different companies have participated in manufacturing and evaluation of the alloy. Engine testing will occur in 2007 with full implementation of the alloy into turbine engines to begin in 2007/2008. Alloy 718Plus will be used in both non-rotating and rotating components in next generation engine designs or to replace incumbent alloys like Waspaloy or René 41 in legacy engines.

### **Acknowledgements**

The authors gratefully acknowledge all of the work and support provided by ATI Allvac's organization in the commercialization of Allvac<sup>®</sup> 718Plus<sup>®</sup> Alloy beginning with the R&D

staff but including Manufacturing, Technology, Product Management and Marketing. Thanks are also due to our colleagues within ATI Allegheny Ludlum for all of their work on 718Plus alloy flat products. Lastly and most importantly, we would be remiss if we didn't acknowledge the contributions of all of the engineers at the turbine engine OEMs and their suppliers who are working so hard to implement the alloy and to the Air Force for their support of several initial evaluation efforts.

## References

- [1] H.L. Eiselstein, "Metallurgy of Columbium-Hardened Nickel-Chromium-Iron Alloy," *Advances in the Technology of Stainless Steel and Related Alloys*, ASTM STP No. 369, 1965, pp. 62-77.
- [2] R.E. Shafrik, D.D. Ward and J.R. Groh, *Superalloys 718, 625, 706 and Various Derivatives*, ed. E.A. Loria, TMS, June 2001, pp. 1-11.
- [3] D.F. Paulonis and J.J. Schirra, *Superalloys 718, 625, 706 and Various Derivatives*, ed. E.A. Loria, TMS, June 2001, pp. 13-23.
- [4] W.D. Cao and R.L. Kennedy, *Superalloys 718, 625, and Various Derivatives*, ed. E.A. Loria, TMS, 1994, p. 463.
- [5] R.L. Kennedy, W.D. Cao, T.D. Bayha, and R.A. Jeniski, "Developments in Wrought Nb Containing Superalloys (718+100°F)," *Niobium for High Temperature Applications*, ed. by Young-Won Kim and Tadeu Carneiro, TMS, 2004, pp. 11-21.
- [6] W.D. Cao and R.L. Kennedy, "Role of Chemistry in 718 Type Alloys—Allvac<sup>®</sup> 718Plus<sup>™</sup> Development," *Superalloys 2004*, Seven Springs Conference, Seven Springs, PA, TMS, 2004, pp. 91-99.
- [7] W.D. Cao and R. L. Kennedy, "New Developments in Wrought 718-Type Superalloys," *Acta Metallurgica Sinica*, Vol. 18, No. 1, February 2005, pp 39-46.
- [8] R.L. Kennedy, "Allvac<sup>®</sup> 718Plus<sup>™</sup> Alloy, Superalloy for the Next Forty Years," *Sixth International Special Emphasis Symposium on Superalloys 718, 625, 706 and Derivatives*, ed. by E. A. Loria, TMS (The Minerals, Metals & Materials Society), Pittsburgh, PA, October, 2005, pp. 1-14.
- [9] W.D. Cao, "Solidification and Solid State Phase Transformation of Allvac<sup>®</sup> 718Plus<sup>™</sup> Alloy," *Sixth International Special Emphasis Symposium on Superalloys 718, 625, 706 and Derivatives*, ed. by E. A. Loria, TMS (The Minerals, Metals & Materials Society), Pittsburgh, PA, October, 2005, pp. 165-177.
- [10] Xishan Xie, Gailian Wang Jianxin Dong, Chunmei Xu, Wei-Di Cao, Richard Kennedy, "Structure Stability Study on a Newly Developed Nickel-Base Superalloy—Allvac<sup>®</sup> 718Plus<sup>™</sup>," *Sixth International Special Emphasis Symposium on Superalloys 718, 625, 706 and Derivatives*, ed. by E. A. Loria, TMS (The Minerals, Metals & Materials Society), Pittsburgh, PA, October, 2005, pp. 179-191.
- [11] Xishan Xie, Chunmei Xu, Gailian Wang, Jianxin Dong, Wei-Di Cao, Richard Kennedy, "TTT Diagram of a Newly Developed Nickel-Base Superalloy – Allvac<sup>®</sup> 718Plus<sup>™</sup>," *Sixth International Special Emphasis Symposium on Superalloys 718, 625, 706 and Derivatives*, ed. by E. A. Loria, TMS (The Minerals, Metals & Materials Society), Pittsburgh, PA, October, 2005, pp. 193-202.
- [12] E.A. Ott, J. Groh, and H. Sizek, "Metals Affordability Initiative: Application of Allvac<sup>®</sup> 718Plus<sup>®</sup> Alloy for Aircraft Engine Static Structural Components," *Sixth International Special Emphasis Symposium on Superalloys 718, 625, 706 and Derivatives*, ed. by E. A. Loria, TMS (The Minerals, Metals & Materials Society), Pittsburgh, PA, October, 2005, pp. 35-46.
- [13] Schlosser Report – Discussion with Sam Aichlmeyer.
- [14] Wei-Di Cao and R.L. Kennedy, "Recommendations for Heat Treating Allvac<sup>®</sup> 718Plus<sup>®</sup> Alloy Parts," Allvac Technical Report, February 24, 2006.

- [15] X.B. Liu, S. Rangararan, E. Barbero, K.M. Chang, W.D. Cao, R.L. Kennedy and T. Carneiro, "Fatigue Crack Propagation Behavior of Newly Developed Allvac<sup>®</sup> 718Plus<sup>™</sup> Superalloy," *Superalloys 2004*, The Seven Springs Conference, Seven Springs, PA, TMS, 2004, pp. 283-290.
- [16] Xingbo Liu, Jing Xu, Nate Deem, Keh-Minn Chang, and Ever Barbero, Wei-Di Cao, R.L. Kennedy, Tadeu Carneiro, "Effect of Thermal-Mechanical Treatment on the Fatigue Crack Propagation Behavior of Newly Developed Allvac<sup>®</sup> 718Plus<sup>™</sup> Alloy," *Sixth International Special Emphasis Symposium on Superalloys 718, 625, 706 and Derivatives*, ed. by E. A. Loria, TMS (The Minerals, Metals & Materials Society), Pittsburgh, PA, October, 2005, pp. 233-242.
- [17] David S. Bergstrom and Thomas D. Bayha, "Properties and Microstructure of Allvac<sup>®</sup> 718Plus<sup>™</sup> Alloy Rolled Sheet," *Sixth International Special Emphasis Symposium on Superalloys 718, 625, 706 and Derivatives*, ed. by E. A. Loria, TMS (The Minerals, Metals & Materials Society), Pittsburgh, PA, October, 2005, pp. 243-252.
- [18] T.D. Bayha, M. Lu and K.E. Kloske, "Investment Casting of Allvac<sup>®</sup> 718Plus<sup>™</sup> Alloy," *Sixth International Special Emphasis Symposium on Superalloys 718, 625, 706 and Derivatives*, ed. by E. A. Loria, TMS (The Minerals, Metals & Materials Society), Pittsburgh, PA, October, 2005, pp. 223-232.
- [19] Reference discussions with Paul Rogers of Carlton.
- [20] Environmentally Friendly Aero Engine Proposal for Framework Programme 6. Section WP4.4 Advanced Hot Structure, March 31st, 2004, pp. 45.
- [21] B.J. Bond and R.L. Kennedy, "Evaluation of Allvac<sup>®</sup> 718Plus<sup>™</sup> Alloy in the Cold Worked and Heat Treated Condition," *Sixth International Special Emphasis Symposium on Superalloys 718, 625, 706 and Derivatives*, ed. by E. A. Loria, TMS (The Minerals, Metals & Materials Society), Pittsburgh, PA, October, 2005, pp. 203-211.
- [22] Ian Dempster, Wei-Di Cao, Richard Kennedy, Betsy Bond, Jose Aurrecoechea, "Structure and Property Comparison of Allvac<sup>®</sup> 718Plus alloy<sup>™</sup> Alloy and Waspaloy Forgings," *Sixth International Special Emphasis Symposium on Superalloys 718, 625, 706 and Derivatives*, ed. by E. A. Loria, TMS (The Minerals, Metals & Materials Society), Pittsburgh, PA, October, 2005, pp. 155-164.
- [23] J. Lemsky. K. Kloske, T. Bayha, and H. Sizek, "Press Forging of Alloy 718Plus<sup>™</sup> (abstract only)," *Sixth International Special Emphasis Symposium on Superalloys 718, 625, 706 and Derivatives*, ed. by E. A. Loria, TMS (The Minerals, Metals & Materials Society), Pittsburgh, PA, October, 2005, pp. 709.
- [24] J. Lemsky. K. Kloske, and T. Bayha, "IsoCon Forging of Alloy 718Plus<sup>™</sup> (abstract only)," *Sixth International Special Emphasis Symposium on Superalloys 718, 625, 706 and Derivatives*, ed. by E. A. Loria, TMS (The Minerals, Metals & Materials Society), Pittsburgh, PA, October, 2005, pp. 711.
- [25] Wei-Di Cao, R.L. Kennedy, "Application of Direct Aging to Allvac<sup>®</sup> 718Plus Alloy<sup>™</sup> Alloy for Improved Performance," *Sixth International Special Emphasis Symposium on Superalloys 718, 625, 706 and Derivatives*, ed. by E. A. Loria, TMS (The Minerals, Metals & Materials Society), Pittsburgh, PA, October, 2005, pp. 213-222.