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Metals Affordability Initiative: Application of Allvac Alloy 718Plus® for Aircraft Engine Static Structural Components

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Abstract

Mechanical property balance, malleability, and weldability of Alloy 718 have driven widespread utilization across the aerospace and non-aerospace industries for nearly 50 years. However, the metastability of the primary strengthening gamma double prime phase is typically unacceptable for applications above about 650°C. As a result, other more costly and difficult to process alloys, like Waspaloy, are used in such applications. The latter alloys, strengthened primarily by gamma prime, are also more sensitive to weld-related cracking than Alloy 718. As part of the Metals Affordability Initiative CORE Program, several alternate alloys were identified and evaluated for aircraft engine static structural component applications for use temperatures of at least 700°C. The application-integrated project team consisting of engine manufacturers, General Electric, Honeywell, and Pratt & Whitney; forgers Firth-Rixson and Ladish Co., Inc.; primary metal producers, Allvac and Carpenter Technology; and the Air Force Research Laboratory, selected the Allvac-developed 718Plus® alloy composition for scale-up and validation. Subscale and full-scale experiments confirmed that processability and weldability of this alloy were significantly improved relative to Waspaloy, approaching that of Alloy 718. Complex rolled rings varying in size from less than 25 to nearly 250 kg have been processed validating the advantages of this alloy. Assessment suggests capability similar to Waspaloy to 704°C has been achieved along with an acceptable balance of other properties. This paper will summarize the processing, weldability, and mechanical property evaluations successfully performed in this project, as well as progress toward industrial implementation of this alloy.

Introduction

Since the advent of the first superalloys over 60 years ago, alloy developers have worked to promote strength and high temperature stability while balancing processability. Processing constraints for many alloy systems preclude their general use for cast and wrought forging applications. Instead these compositions are used in the cast form, or are producible only using powder metallurgy. The development and introduction of alloy 718 in the late 1950's[2] offered a significant breakthrough in malleability and weldability relative to other high strength alloys available at that time including Waspaloy and René 41[1] which are primarily gamma prime strengthened. Since the introduction of alloy 718 a significant number of alloys have been examined, including cast as well as wrought alloys, with the primary intent to maintain or improve properties and provide increased thermal stability while maintaining favorable processability. Some of the alloys[2-10] developed subsequently are shown along with 718,

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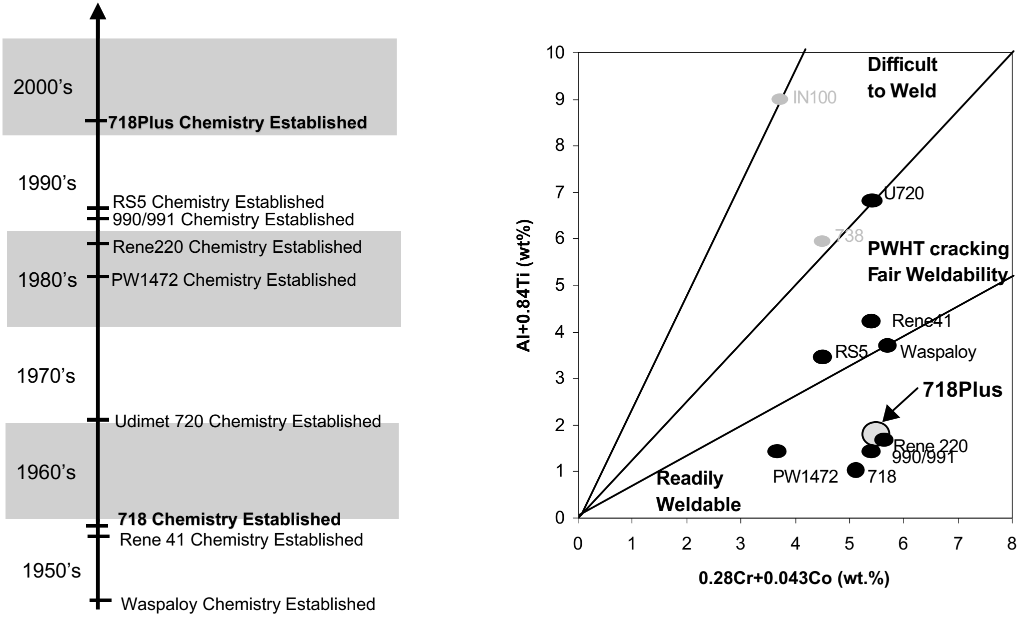
Waspaloy, and René 41 in the development timeline of Figure 1a. A key requirement beyond strength, toughness, fatigue, creep, crack growth resistance, and processability which has also driven composition development is weldability. The relative weldability of various alloys has been graphically represented by Haafkens and Matthey[11], and is modified to display other alloys including 718Plus in Figure 1b.



(a) (b)

Figure 1: (a) Developments leading up to alloy 718 and subsequent efforts to improve capability over 718[1-10], and (b) relative weldability of various superalloys[11] plotted along with anticipated alloy 718Plus behavior based on chemistry.

Most recently, a composition known as 718Plus[12-15], developed ATI Allvac®, has shown exceptional phase stability by reliance on a greater fraction of gamma prime than in alloy 718. Aerospace interest in an alloy which is malleable, weldable, and capable of operating to temperatures of 704°C has led to the selection of the 718Plus composition for scale-up demonstration under a US Air Force Metals Affordability Initiative[16] project for non-rotating, structural components. The focus has been on providing a low cost alternative to alloys such as Waspaloy and René 41 while providing a nominal 50C° temperature capability advantage over alloy 718. As shown in Figure 1b, the 718Plus alloy lies in a composition range where the alloy is also anticipated to be readily weldable. A comparison of nominal compositions of the 718Plus alloy to Waspaloy and 718 is given in Table I for reference. The subscale processing, assessment, and alloy selection performed under this multi-company MAI effort was previously reported[15]. These efforts led to the selection of the 718Plus composition and the selection of a solution and two step age heat treatment. Scale-up and validation efforts including heat treatment, microstructure, and mechanical property assessments have been completed.

Table I: Nominal chemistry of 718Plus compared to 718 and Waspaloy[13] in weight percent.

Alloy	Ni	Cr	Mo	W	Co	Fe	Nb	Ti	Al
718[13]	Bal.	18.1	2.9	-	-	18	5.4	1	0.45
718Plus[13]	Bal.	18	2.8	1	9	10	5.4	0.7	1.45
Waspaloy	Bal.	19.4	4.25	-	13.25	-	-	3	1.3

Experimental Procedure

Rolled rings for evaluation were supplied by Firth-Rixson Viking using double melt (VIM+VAR) ingot melted by ATI Allvac to the nominal chemistry in Table 1 and converted to billet by ATI Allvac or Carpenter Technologies. The various geometries shown in Figure 2[15] include both rings with rectangular cross sections and those with significantly more intricate contour rolled shapes. Rings used by General Electric for heat treatment, mechanical property, and weldability assessments in this effort include the 890mm diameter rectangular ring and 1 meter diameter contour rolled ring geometries.

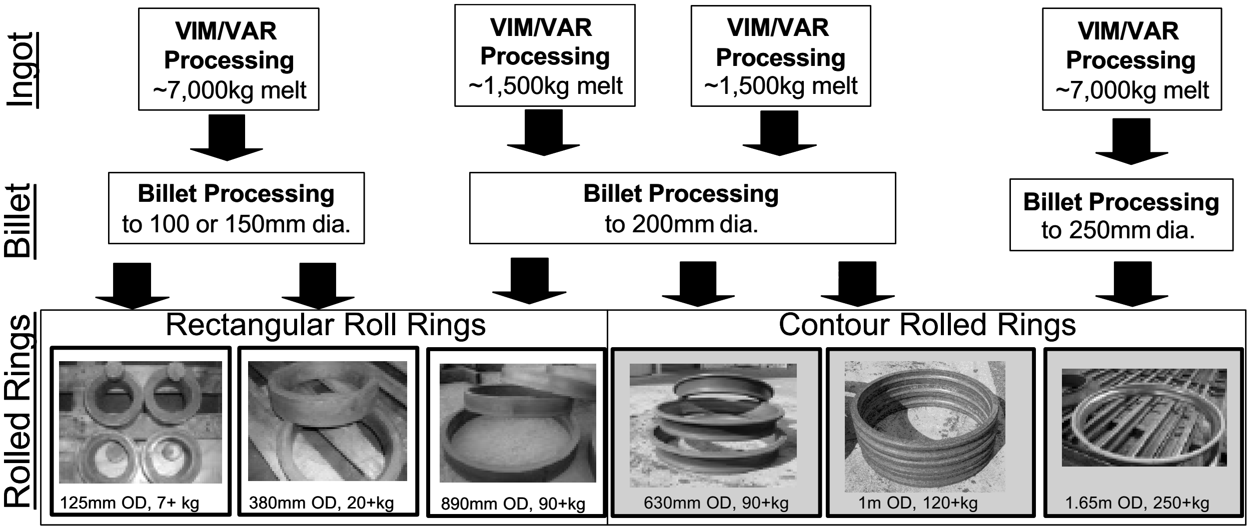


Figure 2: Ingot, billet, and rolled rings produced and evaluated in the MAI project. [15] including approximate product form size scales.

Evaluation of the microstructure and mechanical properties of a nominally 1 meter diameter contour rolled ring generated from 200mm diameter billet, was performed after heat treatment at 982°C for 4 hours followed by polymer quenching and a 788°C/8hr/furnace cool primary age and a 704°C/8hr/air cool secondary age sequence. Microstructures were evaluated in 10 locations on two diametrically opposed cross sections. Grain sizes were evaluated according to the Heyn intercept method of ASTM E-112, and nominal and as-large-as (ALA) grain sizes were also reported. Mechanical test specimens were extracted such that the long axis of the specimen was oriented in the tangential direction. Tensile testing was performed at ambient and elevated temperatures. Strain controlled low cycle fatigue testing was performed at 454°C and 704°C under A=1 loading conditions.

Detailed assessment of the sensitivity of the alloy to typical industrial heat treatment processing window tolerances was performed using 890 mm diameter rectangular ring material. Heat treatment blanks 100mm long by 15mm square were extracted tangentially to cover test bar manufacture. A full factorial heat treatment design of experiments (DOE) was conducted with three variables: solution temperature, cooling rate from solution temperature, and primary age temperature, at two levels and a center point. Two additional conditions were also incorporated in this study to assess edge of envelope processing. A summary of the conditions tested is depicted in Figure 3. Samples were instrumented with embedded thermocouples and cooled on specialized cooling fixtures developed to achieve target heat treatment temperatures and cooling rates from the solution temperature. Ambient and 704°C tensile testing was performed in duplicate for each heat treatment condition. Statistical analysis of mechanical property data was performed using Minitab software. Microstructure assessment and grain size evaluation was also performed on samples prepared by conventional mechanical polishing and etching followed by optical microscopy. Solution treatment temperatures were 968°C +/- 14C°, primary age temperatures were 788°C +/-14C°, and the cooling rates from the solution temperature were approximately 100C°+/-50C°/minute as measured between 927°C and 760°C to simulate the range of quench rates anticipated for production size components. The center point of the solution temperature DOE was selected to be 968°C rather than 982°C to minimize concerns relative to extensive resolutioning of the grain boundary phase. An additional hardness assessment as a function of primary and secondary aging time was conducted using 10-20mm heat treatment cubes solution treated at 968°C for 1 hour and quenched at about 100C°/minute followed by aging at 788°C and 704°C for various times. Macro hardness was measured on the Rockwell C scale.

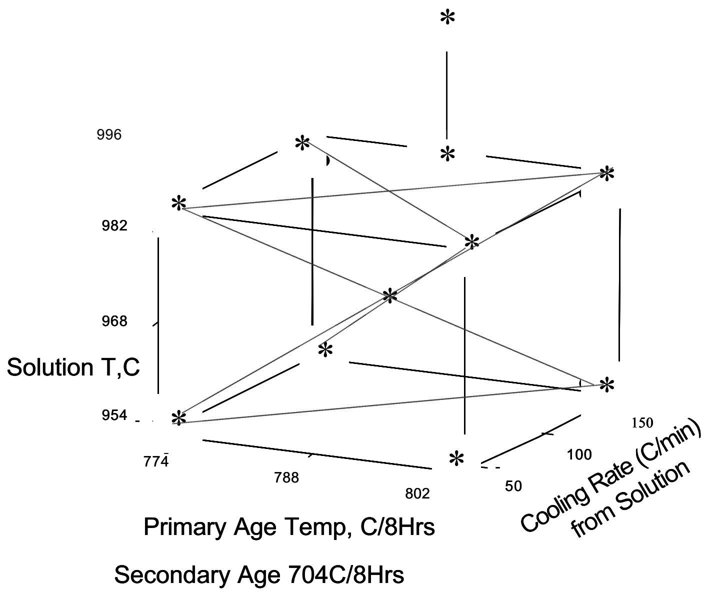
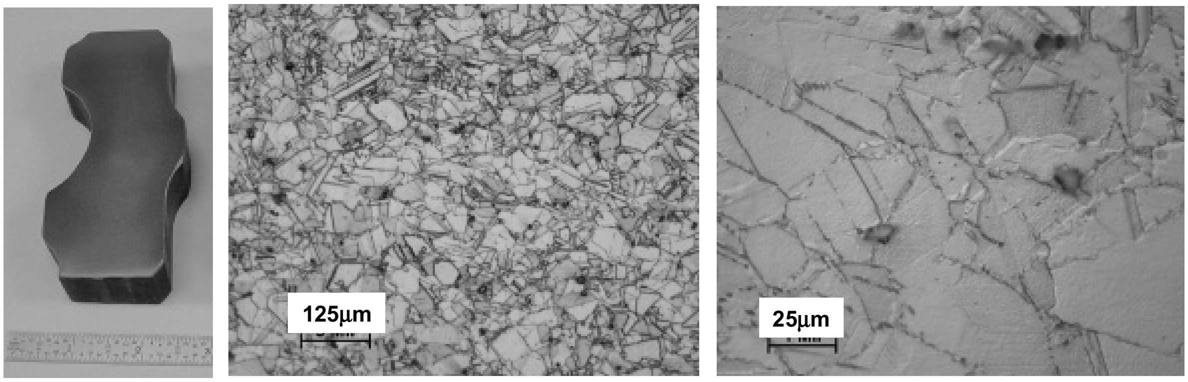


Figure 3: Heat treat sensitivity DOE schematic and summary of nominal conditions.

Assessment of production size, rolled ring electron beam (EB) weldability was performed using the nominal 890 mm diameter ring geometry. Welds samples were made by cutting a ring at mid height to form two full diameter rings. Adjacent surfaces were prepared for autogenous EB welding in a simple 6.4mm thick square butt joint configuration using conventional machining. Rings were subsequently tack welded intermittently along the outside diameter of the joint by gas tungsten arc welding using alloy 718 filler wire. Similarly processed 718 and Waspaloy rings were prepared in parallel to serve as a baseline for EB weld comparison. EB welding was performed for 718Plus and the baseline 718 and Waspaloy rings in the solutioned or solutioned and stabilized heat treatment condition. Welding was performed with parameters typical for 718 without filler metal. Following full penetration EB welding along the full circumference of the ring and a subsequent cosmetic weld pass, rings were inspected by visual, fluorescent die penetrant (FPI), and x-ray methods consistent with ASTM E1417 and E1742 specifications. FPI was conducted via type 1, method A, sensitivity level 3 parameters. Full diameter rings were subsequently age heat treated and re-inspected. Metallographic cross sections were taken from each weld in a typical location and were prepared using conventional mechanical polishing and etching for assessment of weld quality.

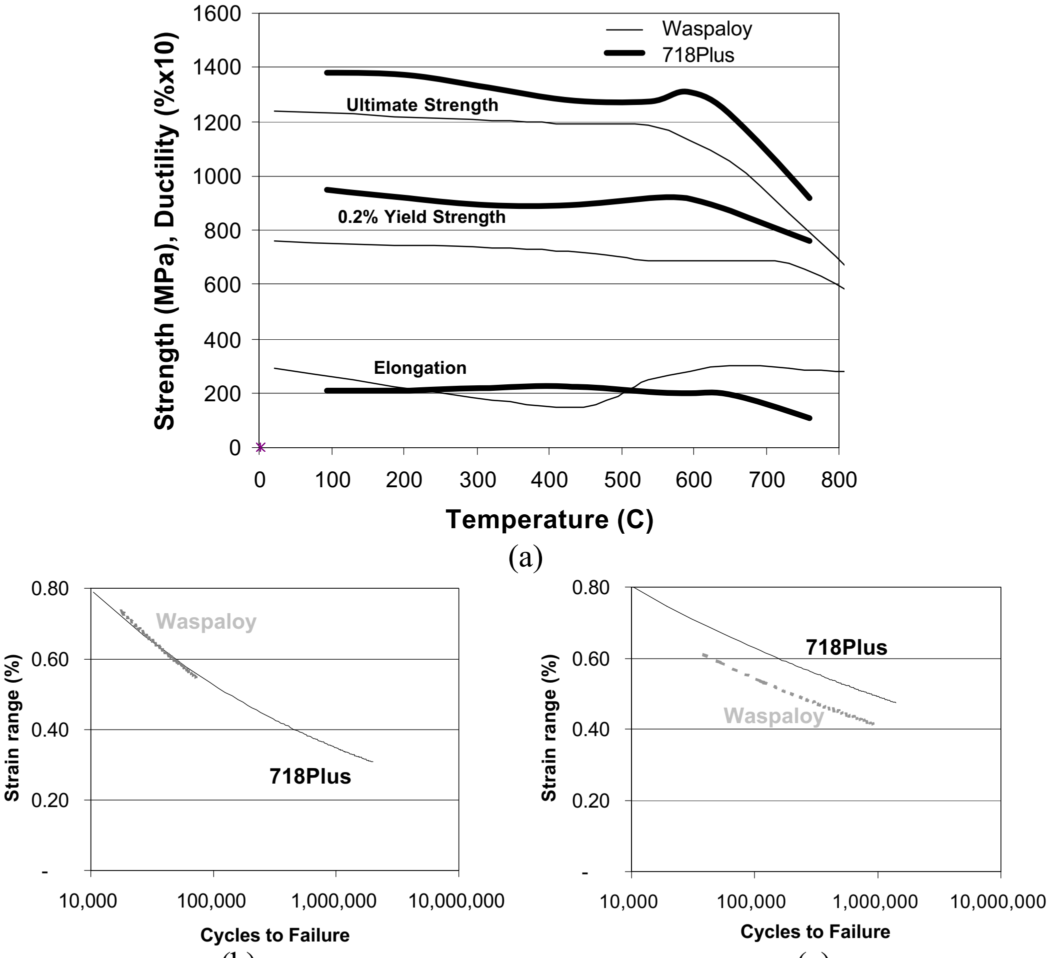
Results and Discussion

Macrostructural and microstructural assessment of the nominal 1 meter diameter contour ring after solution and age heat treatment is shown in Figure 4. The etched macrostructure of the ring cross section (Figure 4a) is highly uniform across the entire contour section. Assessment of the microstructure shows a uniform recrystallized structure with an average grain size of ASTM 5.7 with grains as-large-as (ALA) 3.0. A higher magnification micrograph in Figure 4c shows the presence of primary carbides and grain boundary phase decoration. Tensile strengths meet or exceed that of Waspaloy as shown in Figure 5a. Comparison of the strain controlled low cycle fatigue behavior in Figure 5b and c indicates that 718Plus meets or exceeds the low cycle fatigue performance typical of Waspaloy as well.



(a) (b) (c)

Figure 4: Typical structure of 1 meter diameter ring after heat treatment at 982°C for 4 hours followed by aging showing a (a) uniform macro and microstructure at (b) low and (c) high magnification.



(a)

(b) (c)

Figure 5: Properties of 718Plus - (a) tensile compared to that of Waspaloy[17] and strain controlled low cycle fatigue at (b) 454°C and (c) 704°C compared to similar Waspaloy baseline tests[15].

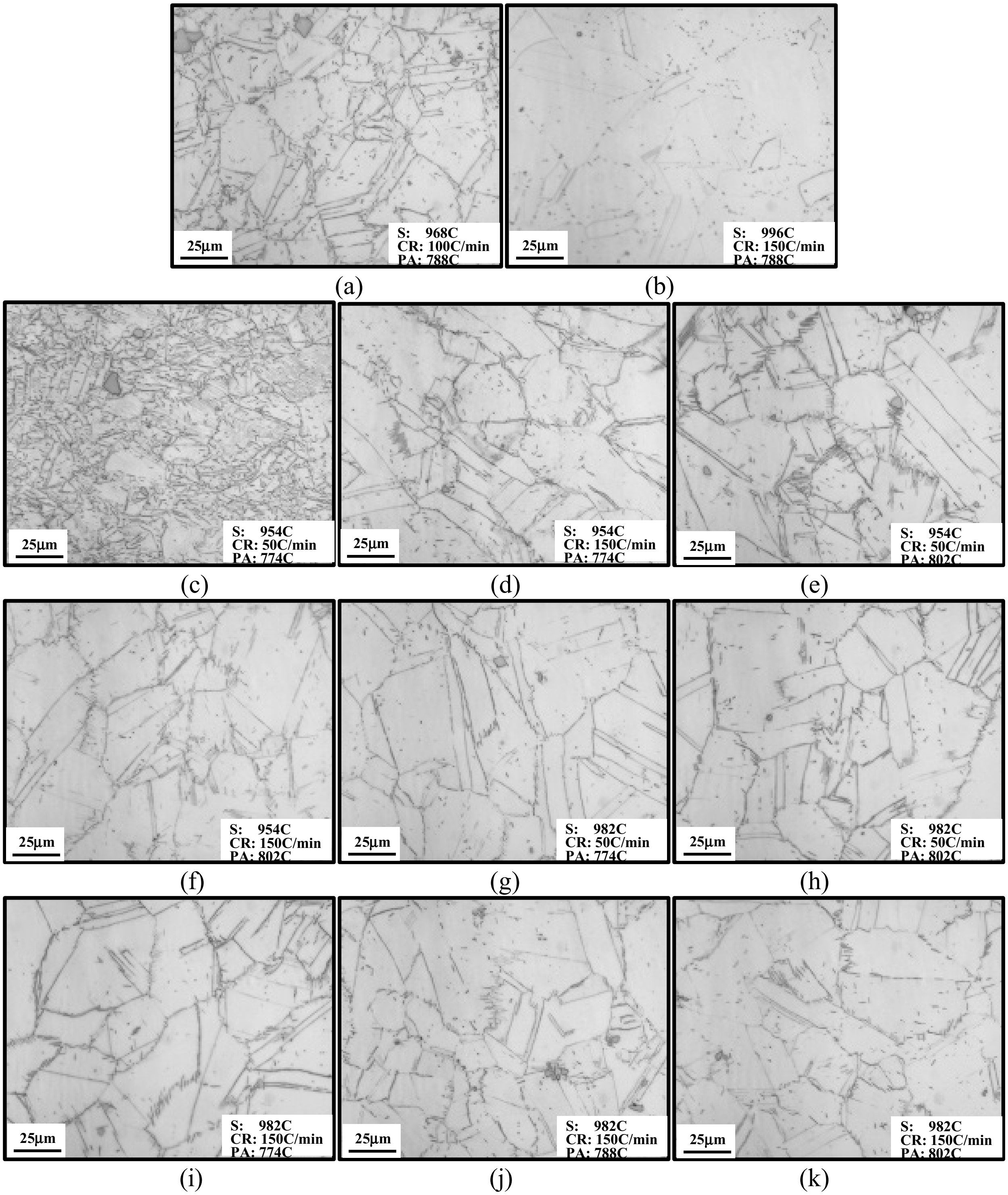
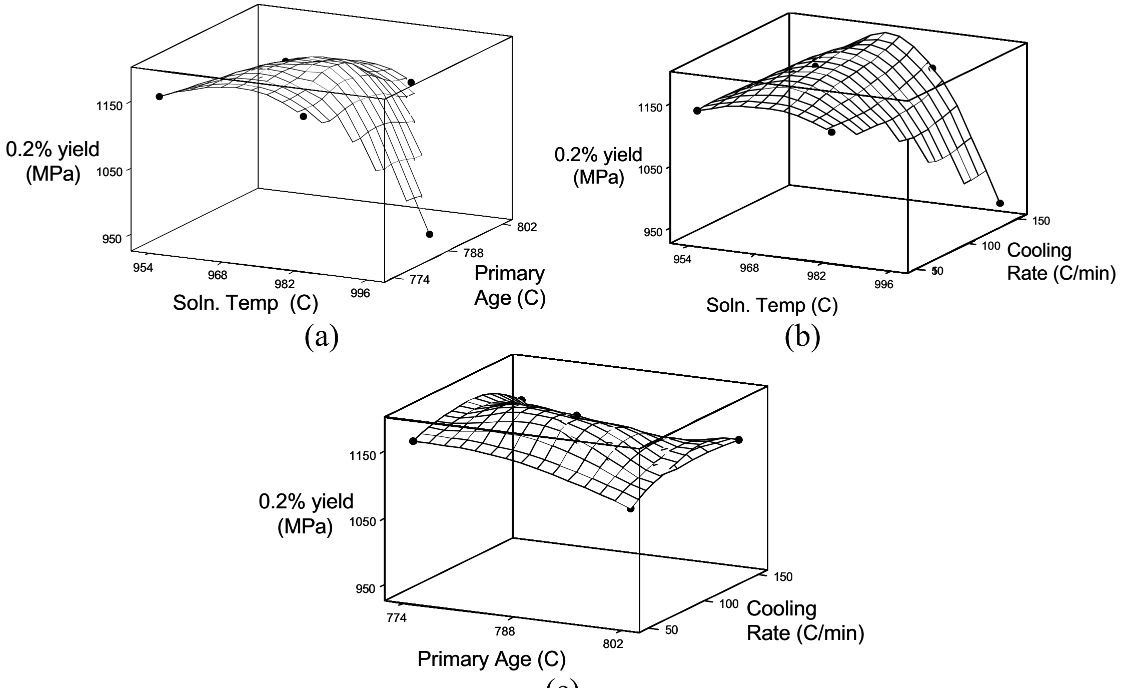


Figure 6: Microstructures for each condition in the heat treat sensitivity DOE. Note that all samples have also received a subsequent 704°C secondary age for 8 hours.

The sensitivity of the alloy microstructure and tensile behavior to typical tolerances on solution, quench, and age heat treatment were investigated. Microstructural assessments for each of the 11 conditions are shown in Figure 6. Each condition includes a solution, primary age, and a common 704°C 8 hour secondary age. The DOE center point and intended heat treatment specification corresponds to the condition in Figure 6a. Solution treatment at temperatures significantly above that of the 968°C center point and outside that of a typical solution heat treatment temperature tolerance, such as 996°C (968°C+28C°) in Figure 6b, results in significant dissolution of the grain boundary phase and apparent grain growth. Such conditions could lead to notch sensitivity and reduced crack growth resistance and should generally be avoided in standard heat treatment of this alloy. Lower solution temperatures such at 954°C tend to result in larger amounts of grain boundary phase decoration as shown in Figures 6c through f. When paired with a low cooling rate from the solution temperature and a lower primary age temperature, the 954°C solution temperature can lead to significant intragranular and grain boundary precipitation as is evident in Figure 6c. However, generally all conditions within the tolerance of normal heat treatment and ring quenching practice result in similar microstructures (Figure 6 with the exception of 6b) containing grain sizes in the range of ASTM 5-7 and moderate grain boundary phase decoration. Such structures are comparable to characteristics considered favorable in alloy 718.

The effect of heat treatment on the 0.2% yield strength at ambient and 704°C testing temperatures was assessed. Yield strengths were not strongly dependent upon the solution and primary age temperatures within the range of +/-14C° of the heat treatment center point (968°C solution and 788°C primary age) as shown in Figure 7a and 8a. Solution temperatures above this range (996°C) result in reduced yield strength at both test temperatures as shown in Figures 7a and b and 8a and b. Some variation in strength as a function of cooling rate is observed both at ambient and 704°C test temperatures as shown in Figures 8b and c and 8b and c. Overall the yield strength variation within the tolerance of normal heat treatment and ring quenching practice is within less than 2 standard deviations of the average.

The dependence of average hardness on the primary and secondary age times was assessed after solution treating at 968°C followed by cooling at about 100C°/minute. The as-solutioned and quenched hardness was measured as 39 Rc. Primary and secondary age temperatures were set to 788°C and 704°C, respectively. As shown in Figure 9, hardness values reach or exceed approximately 45Rc for most age conditions with 2 hours or more at 788°C and 4 hours or more at 704°C. All conditions within the tolerance for a typical aging time heat treat specification result in hardness levels of at least 45 Rc.

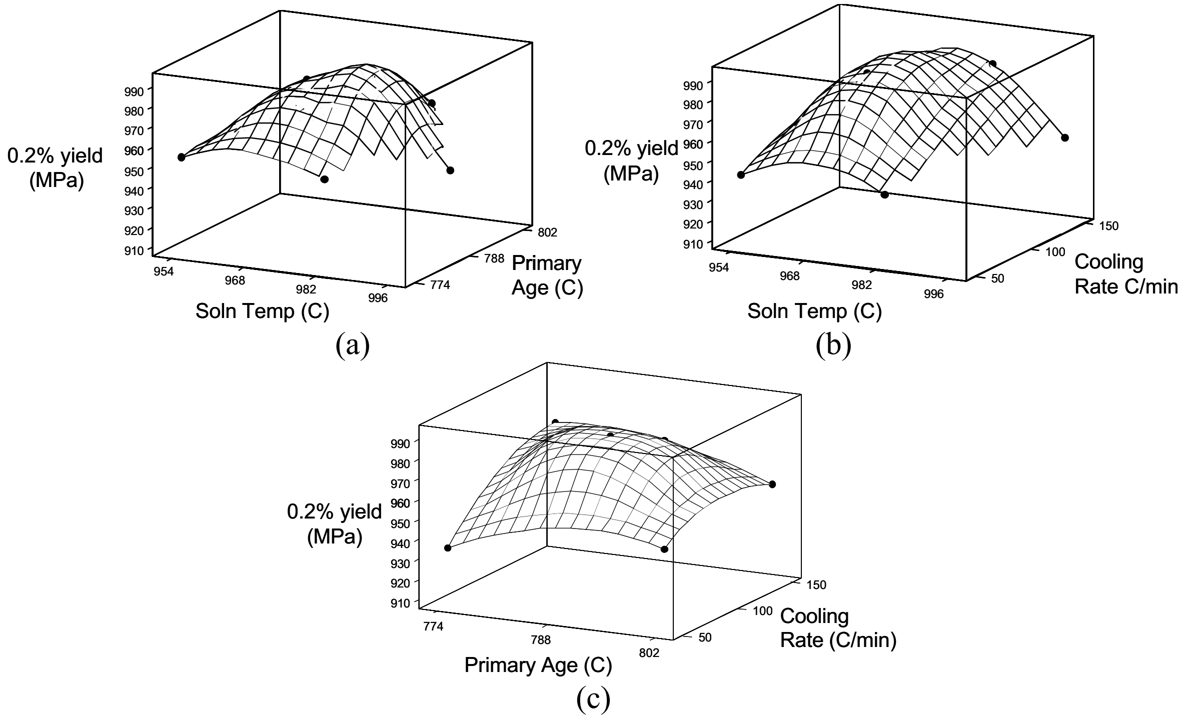


(a)

(b)

(c)

Figure 7: 718Plus ambient temperature 0.2% offset yield strength behavior versus solution temperature, cooling rate, and primary age temperature.



(a) (b)

(c)

Figure 8: 718Plus 704°C 0.2% offset yield strength behavior versus solution temperature, cooling rate, and primary age temperature.

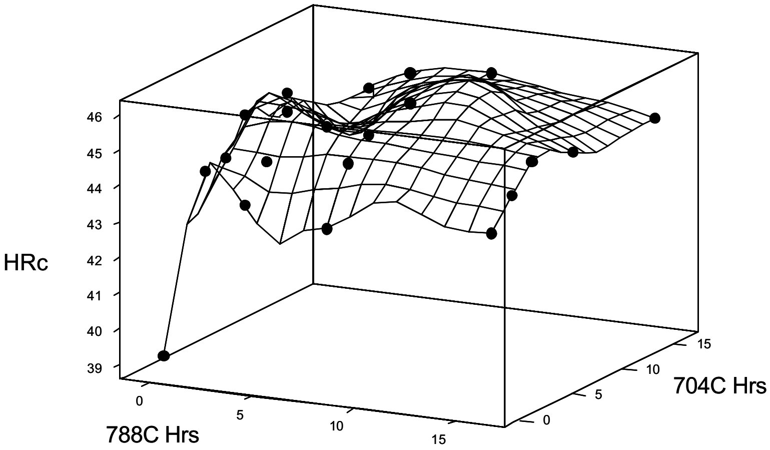
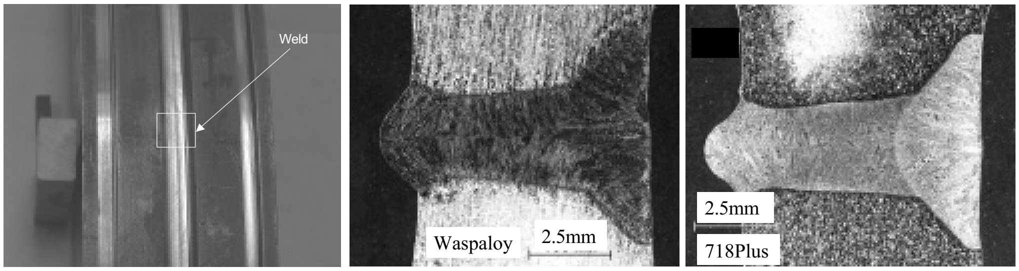


Figure 9: 718Plus aging time sensitivity study after solution treatment at 968°C for one hour.

An assessment to compare the weldability of 718Plus rings to 718 and Waspaloy was conducted via EB welding in the solution or solution and stabilized condition of each alloy. A macroscopic photograph showing the weld location as viewed from the outside diameter is shown in Figure 10a. Microstructures typical of full penetration electron beam welds were found on polished and etched cross sections, also shown in Figure 10. No microstructural evidence of fusion zone or heat affected zone cracking was evident in the 718Plus material. Non-destructive inspection in the as-welded and in the welded and aged condition is summarized in Table II. No indications were detected in either the 718 or 718Plus welds. A linear indication was reported via x-ray inspection in the Waspaloy ring after welding and aging. Efforts to destructively evaluate the region corresponding to the indication were not successful and the nature of the indication was not determined. Welding trials on full production-scale ring sizes validates that the weldability of the 718Plus alloy is similar to that of 718.



(a) (b) (c)

Figure 10: EB welding of 890 mm diameter rolled rings, (a) typical weld location for 718, Waspaloy, and 718Plus welds and typical welds for (b) Waspaloy, and (c) 718Plus.

Table II: Comparison of weld inspection results for 718, Waspaloy, and 718Plus alloys.

Condition and Alloy	Visual	FPI	X-ray
As welded 718	Acceptable	Acceptable	Acceptable
As welded Waspaloy	Acceptable	Acceptable	Acceptable
As welded 718Plus	Acceptable	Acceptable	Acceptable
Welded + aged 718	Acceptable	Acceptable	Acceptable
Welded + aged Waspaloy	Acceptable	Acceptable	Linear indication
Welded + aged 718Plus	Acceptable	Acceptable	Acceptable

Results of this study validate that the 718Plus alloy can be processed into production-scale rolled rings that exhibit behavior adequate for replacement of many Waspaloy-type component applications. Microstructures, yield strengths, and hardness achieved within the typical heat treatment and ring quenching processing parameter window also validate production robustness of the alloy. Indication-free welds have been produced using production-scale component geometries. Tensile data generated as part of this effort is being used in combination with other MAI-generated data in setting specification limits for this alloy. Efforts are underway using these limits and appropriate processing parameters in an AMS specification being submitted for approval for the 718Plus alloy. Since the physical metallurgy and transformation behavior of this 718Plus alloy have not been fully characterized, continued efforts to understand the effect of forging conditions and as-forged microstructure on the microstructure and properties of this alloy are needed. A more detailed assessment and identification of the precipitate phase constituents of this alloy will be helpful in assessing processing-microstructure-property relations.

Conclusions

Based on the technical efforts in this publication the following conclusions were made:

1. A multi-company / USAF Team working under the Metals Affordability Initiative has identified the ATI Allvac 718Plus alloy as a 704°C alternative to Waspaloy, and has successfully produced production-scale ingot, billet, and rolled rings to verify processing and behavior characteristics.
2. The target heat treatment for 718Plus is a 968°C solution followed by cooling at 100C°/min followed by a 788°C primary age for 8 hours and a 704°C secondary age for 8 hours.
3. Assessment of the tensile and low cycle fatigue behavior of the 718Plus alloy demonstrates capability comparable or improved relative to Waspaloy up to 704°C.
4. A study of the sensitivity of the microstructure and yield strength on the heat treatment conditions indicates that microstructures with an ASTM 5-7 grain size, adequate grain boundary phase decoration, and ambient and 704°C yield strengths less than two standard deviations away from the average value can be obtained within a typical production

rolled ring heat treatment tolerance range. Hardnesses of 45 Rc also are developed with primary aging times above 2 hours and secondary age times of 4 hours and above.

5. Weldability of production-scale 718Plus seamless rolled rings has been validated through electron beam welding resulting in no weld indications in the as-welded and welded and aged condition.
6. A more thorough understanding of the complex physical metallurgy of the 718Plus alloy is still needed to identify the grain boundary phases and intragranular strengthening precipitates as well as to characterize the dissolution and precipitation transformation behavior during thermal and thermomechanical treatment.

Acknowledgements

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