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INVESTMENT CASTING OF ALLVAC® 718PLUS™ ALLOY

T. D. Bayha[1], M. Lu[2] and K. E. Kloske[3]
[1] ATI Allvac, an Allegheny Technologies Company, 2020 Ashcraft Ave, Monroe, NC 28110, USA
[2] PCC Structurals, Inc, 4600 S.E. Harney Drive, Portland, OR 97206, USA
[3]Pratt and Whitney Engines, Aircraft Road, M/S 403-35, Middletown, CT 06457, USA

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Abstract

Many jet engine structural components are fabricated using investment castings, generally a lower-cost material alternative to built-up structures. Waspaloy is a nickel-base, age-hardenable superalloy with excellent high-temperature strength and good oxidation resistance, utilized in rotating aero engine components up to 704°C and higher temperatures for static components in modern jet engines. Typical applications include casings, frames and rings. Waspaloy has improved temperature capability, but suffers from producibility issues such as poor weldability and hot tear resistance. Additionally, the raw materials for Waspaloy are significantly more expensive than those for other casting alloys. Allvac® 718Plus™ alloy was developed as a cast-wrought material with elevated temperature mechanical properties roughly equivalent to those for alloys such as Waspaloy at a significantly lower cost. Cast/wrought 718Plus also has formability and weldability characteristics that are very comparable to alloy 718. Previous ATI Allvac evaluation of 718Plus alloy cast-to-size test bars provided tensile strengths of approximately 690 MPa at 704°C. An evaluation of the producibility of investment cast alloy 718Plus components is necessary to determine suitability for Waspaloy replacement in high performance aero engines. The objective of this work is to evaluate and compare the castability of model components of 718Plus alloy to Waspaloy. Generic molds to compare the fill, hot tearing and weldability of the two materials were investment cast and processed. Samples were excised from the castings and tested mechanically and compared to program goals.

Introduction

The design and construction of advanced aero engines capable of meeting the demands of cost, performance and efficiency are always constrained by material challenges. Waspaloy is a current alloy utilized in elevated temperature investment casting applications. Inconel alloy 718 is the most extensively used [1, 2] cast superalloy due to its excellent balance of cost, processability (including weldability) and high temperature engineering capability. Applications of alloy 718 are typically restricted to about 649°C as above this temperature the γ" (Ni_3Nb) strengthening phase overages, and properties, particularly creep resistance, fall dramatically. Cast Waspaloy offers good temperature capability and has been used extensively by Pratt & Whitney in structural applications requiring temperature capability in excess of alloy 718. However, there are several drawbacks associated with Waspaloy as well as other materials within the γ' strengthened class of alloys including reduced processability, increased raw material cost and lower intermediate temperature properties. Despite the improvements in chemistry and processing to make Waspaloy more weldable and processable, there is still a significant need for a weldable and castable structural alloy for high temperature applications.

There are a number of structural applications within aircraft engines that drive the processability requirements in addition to a necessary combination of material properties and high temperature capability. Pratt & Whitney has used cast Waspaloy extensively for such applications in the combustor and turbine sections of the engine, the most common being diffuser cases, tangential out board injectors, and turbine exhaust cases. Typically, part geometry dictates that it be a casting. For cast/wrought assemblies, structural castings need to be welded both during the original processing as well as for repair in service. In addition to the processability drivers, these applications require the material to have adequate high temperature capability and balanced material properties. High temperature capability is critical because a less capable material requires more cooling air, lowering overall engine efficiency. Balanced strength, creep, fatigue and crack growth resistance are also critical because they directly impact the weight of the part.

Although cast Waspaloy has historically been used in these applications because of its temperature capability, it has several drawbacks. The low and intermediate temperature strength of Waspaloy is low when compared to materials such as alloy 718 resulting in increased component weight for some intermediate temperature areas. In addition, cast Waspaloy exhibits an increased propensity to hot tears, requiring more re-work during manufacturing and requires some components to be made of multi-part assemblies instead of as single piece castings. Waspaloy is also prone to cracking in the fusion zone during welding. While the weldability problems can be mitigated during the original part manufacturing, it can present difficulties in service. Finished parts are more difficult to weld because they are in the fully heat-treated condition; and re-solutioning to improve weldability can cause distortion of the finished parts. For comparison it is feasible to weld repair alloy 718 in the fully heat treated condition.

There have been two approaches to abate the weldability problems of cast Waspaloy; the first was by modifying chemistry and the second by modifying the processing. Pratt & Whitney's chemistry modifications have centered on better control of interstitial and trace elements. A cleaner material is more readily weldable without substantially impacting other material properties. Another approach has been to use alternate filler wire such as alloy 625 or to modify the heat treatment for superior weldability. However, modified heat treatments cannot be used in repair applications and the use of alternate filler wire frequently can cause problems with the crack growth resistance and creep resistance due reduced material properties.

Despite its limitations, Waspaloy is still frequently used in many different applications because the alternative alloys have greater limitations. High temperature capable alloys have reduced castability for structural applications and are not weldable using traditional techniques. The most viable candidate, Incoloy 939, can be welded, but it suffers many of the same processing difficulties as Waspaloy. There is a need for an alloy that has higher strength than Waspaloy and maintains its excellent properties and processing characteristics. Allvac® 718Plus™ alloy meets this need. The new alloy shows excellent hot-workability and weldability and better stress rupture and creep properties at 704°C than Waspaloy in forgings [3]. Only a small drop in mechanical properties is observed after long-term thermal exposure up to 760°C.

The use of 718Plus alloy in elevated temperature applications is of interest for military systems. Initial characterization shows that the alloy exhibits many similarities to alloy 718, including good workability, weldability and intermediate temperature strength capability. ATI Allvac has extensively investigated the 718Plus alloy wrought properties, both as an internal program and as part of the Metals Affordability Initiative program entitled "Low-Cost, High Temperature Structural Material" for turbine engine ring-rolling applications [3-6]. The objectives of these programs are to develop an alloy composition with the following characteristics:

- 38°C operating temperature advantage over alloy 718
- Improved thermal stability; equal to Waspaloy at 704°C
- Good weldability; at least intermediate to alloys 718 and Waspaloy
- Minimal cost increase; intermediate to alloys 718 and Waspaloy
- Good workability; better than Waspaloy

An ATI Allvac internal program has evaluated 718Plus alloy for suitability in investment casting applications. Property goals for the program were chosen with consultation from Pratt & Whitney. Essentially, equivalence with current alloys utilized in high temperature applications, such as Waspaloy and IN 939, is desired. Cast-to-size (CTS) test bars were cast and HIP'ed to a standard 718 alloy HIP cycle (1163°C/103 MPA/3hr). A heat treatment study was conducted and a heat treatment cycle of 954°C/1hr+788°C/8hr+649°C/8hr was chosen. The bars heat treated to this condition had the best combination of tensile and stress rupture properties and led to the establishment of property goals for 718Plus alloy cast materials. The room temperature and elevated temperature tensile property goals are presented in Table I.

Table I. Tensile Property Goals for 718Plus™ Alloy Investment Castings

Test Temperature °C	**Ultimate Strength MPa**	**Yield Stress MPA**	**Elongation %**	**Area Reduction %**
20	1103	827	10	15
649	862	690	10	15
704	690	621	10	15

The 718Plus alloy composition is shown in Table II, compared to nominal chemistries of alloys 718 and Waspaloy. The principal differences in the 718Plus alloy chemistry are the increase in total Al+Ti content, Al/Ti ratio, and the addition of Co and W. The 718Plus alloy nominal composition was slightly modified for this study; the casting composition chosen has an additional 0.2 $^{w}/o$ of both Al and Ti over the nominal wrought alloy composition.

Table II. Chemistry Comparison of Alloys 718, Waspaloy and 718Plus™

Alloy	**Chemistry**											
	Ni	**Cr**	**Co**	**Mo**	**W**	**Nb**	**Al**	**Ti**	**Fe**	**C**	**P**	**B**
718	52.5	19	–	3.0	–	5.1	0.5	0.9	18.5	0.04	0.007	0.004
Waspaloy	58.7	19.4	13.3	4.3	–	–	1.3	3.0	–	0.035	0.006	0.006
718Plus	52.0	18.0	9.5	2.7	1.0	5.4	1.45	0.75	9.5	0.020	0.006	0.005

The objective of this work is to evaluate the castability of 718Plus alloy relative to Waspaloy currently utilized in the elevated temperature aero engine applications. Universal Technology Corporation (UTC), as part of an Air Force Research Laboratory-funded Technical Operations Support (TOPS) Contract, funds the program. The program team for this task is comprised of ATI Allvac, PCC Structurals, Inc. (Portland, OR) and Pratt and Whitney, (East Hartford, CT).

Technical Approach

ATI Allvac provided 718Plus alloy ingot (heats WN71 and WN72) to PCC Structurals, Inc. for remelting into investment castings. PCC cast both the 718Plus alloy and Waspaloy material for melting into several proprietary evaluation mold configurations to evaluate the suitability of 718Plus alloy for use as an investment-casting alloy. PCC utilized their non-concentric ring mold, hot tear mold, weld mechanical ring mold and test bar mold to produce sufficient castings for evaluation by the program team. These molds measure basic properties needed to facilitate manufacturing of meaningful investment cast components. Based on castability and weldability trials/assessments and outcome of the testing, P&W will define potential part applications in their military engine product line for future study.

Castability Results

Non-Concentric Ring Evaluation

The non-concentric ring mold is a comparative sample used to judge fill and feeding distances on new and modified alloys. Figure 1 shows both a 718Plus alloy and a weldable Waspaloy ring produced in this study. Fluorescent penetrant inspection (FPI) was conducted on both non-concentric rings in their as-cast conditions. In both cases, no FPI indications were found on the thick wall. In the thin wall, weldable Waspaloy shows a tendency of through wall hot tearing at the joint of ribs and the wall, while the 718Plus alloy casting shows that hot tearing tends to occur at the end of the thin wall. This reveals different feeding characteristics of the two alloys. 718Plus alloy seems to have a shorter feeding distance than weldable Waspaloy. However, within its feeding distance, 718Plus has a more effective feeding capability, which prevents the hot tear occurrence in those areas where hot tears are normally observed.

X-ray inspection was conducted on both the 718Plus alloy and weldable Waspaloy non-concentric rings in the fully heat treated condition. Shrinkage and hot tears were observed in both rings. The results do not indicate one material is significantly better than the other in X-ray quality. More dirt indications were observed in 718Plus ring. This could be related to the mold preparation, casting conditions or ingot quality.

Figure 1. 718Plus alloy (right) and weldable Waspaloy (left) non-concentric rings.

A metallography study was conducted on both non-concentric rings, and the no-fill percentage on thin wall and thick wall was calculated. Both alloys filled the thick wall 100%, while less than 1% of no-fill is observed on thin walls. Microshrinkage (which cannot be seen in X-ray), average grain size, maximum grain size, and typical microstructure of four locations were investigated. Results in Table III show very little microshrinkage was observed in the 718Plus alloy mold and the average and maximum grain size was smaller than those of Waspaloy. This is likely influenced by both the alloy composition and the casting conditions.

Table III. Summary of Non-Concentric Ring Metallography Report

718Plus™ Alloy			
Sample Location	**Max. % Shrinkage**	**Average Grain Size, mm**	**Maximum Grain Size, mm**
A-1 thick wall	<0.5%	0.84	7.75
A-2 thin wall	<0.5%	0.33	5.08
A-3 thin wall	<0.5%	0.38	5.94
A-4 thick wall	<0.5%	0.74	5.61
Weldable Waspaloy			
Sample Location	**Max. % Shrinkage**	**Average Grain Size, mm**	**Maximum Grain Size, mm**
A-1 thick wall	1.2%	1.27	12.19
A-2 thin wall	None	0.51	8.13
A-3 thin wall	None	0.51	6.35
A-4 thick wall	0.2%	1.27	10.41

Hot Tear Mold Evaluation

The hot tear mold is used to assess the propensity of an alloy to form and propagate hot tearing. The two longest arms of the 718Plus hot tear mold were broken in the as-cast condition. Visually, 718Plus alloy appears to be more hot tear prone than weldable Waspaloy.

To quantitatively evaluate the hot tear propensity of the two alloys, FPI inspections were conducted on the molds. FPI maps of both alloys were generated and, hot tear occurrence and total hot tear length were counted on all arms. The results are listed in Table IV for the two materials.

From Table IV, it can be seen that, in terms of total hot tear occurrence and total hot tear length, there is no significant difference between the two alloys. The 718Plus alloy mold shows very few hot tears in arms up to 8¾", while weldable Waspaloy mold shows less tearing tendency in longer arms.

Table IV. Summary of Hot Tear Occurrence and Length for Alloy 718Plus and Weldable Waspaloy

	718Plus™ Alloy		**Weldable Waspaloy**	
	Hot Tear #	**Hot Tear Length**	**Hot Tear #**	**Hot Tear Length**
76 mm Arm	0	0	1	1.1 mm
121 mm Arm	0	0	2	2.5 mm
171 mm Arm	6	31.9 mm	8	27.2 mm
222 mm Arm	0	0	8	74.9 mm
283 mm Arm	7	86.4 mm	1	63.5 mm
343 mm Arm	11	101.6 mm	10	85.9 mm
394 mm Arm	11	101.6 mm	1	63.5 mm
Total	**35**	**321.5 mm**	**31**	**318.6 mm**

Weld Mechanical Ring Evaluation

Weld mechanical rings are utilized to assess the weldability and measure post-weld properties of candidate alloys. Specimens are extracted to assess both partial and full weld properties. Both 718Plus alloy and weldable Waspaloy weld mechanical rings were welded in a normal bench weld condition. Allvac supplied a spool of 1.14 mm 718Plus alloy filler wire for use in the program. Since 718Plus alloy weld wire had not been made before, this material represented a non-routine manufacturing route and welding results showed the wire to be "extremely dirty." This is believed to be representative of the manufacturing practice and not the alloy. PCC's standard 1.57 mm production weldable Waspaloy filler wire was used to repair the weldable Waspaloy weld mechanical ring.

FPI inspection was conducted in the as-cast condition for both the 718Plus alloy and weldable Waspaloy weld mechanical rings. With both alloys, minor shrink porosities and dirt were observed on the ring. These FPI indications were cleaned before welding. FPI and X-ray inspections were conducted again after the welding to ensure good welds. Figure 2 shows the 718Plus weld mechanical ring welded in the both post-hip "soft" condition and post-hip hard condition. Standard test bars were excised from the weld areas, and Bodycote's Materials Testing Lab conducted room temperature tensile testing to assess weld properties.

(a) (b)

Figure 2. 718Plus™ alloy weld mechanical ring samples: (a) welded in the post-hip "soft" condition; and (b) welded in the post-hip "hard" condition.

For comparison to the 718Plus alloy material, a fully heat-treated weldable Waspaloy weld mechanical ring was also sent to the Lab for testing. Figure 3 shows the photo of the weldable Waspaloy weld mechanical ring, and Table VII lists the room temperature tensile results of the weldable Waspaloy welds. In general, the strength of the welded 718Plus alloy was higher than for the Waspaloy material, with slightly lower ductility. The data exhibits some variability, likely due to the lack of quality weld wire. Future work will include welding of another weld mechanical ring with weld wire that meets specification and comparative testing.

Table VI lists the room temperature tensile results of the 718Plus alloy welds. In general, full welds usually have more consistent properties than partial welds, as the partial welds tend to have more heat affected zone defects. Full welds have a finer grain size than base metal and are more microstructurally homogeneous than the combination of partial welds plus base metal. They are also consistently higher in strength, reflecting partial aging from the repeated weld passes.

Figure 3. Weldable Waspaloy weld mechanical ring.

Table VI. Room Temperature Tensile Results for 718Plus™ Alloy Welds

Post Weld "Soft" Condition					
Specimen ID	**Weld**	**Yield Stress MPa**	**Ultimate Strength MPa**	**Elongation %**	**Area Reduction %**
1	Partial	854	1035	6.5	13
2*	Full	984	1108	2.9	3.0
3*	Partial	747	756	2.1	4.5
4*	Full	986	991	0.6	0
5*	Partial	852	1026	4.5	5.5
6	Full	983	1069	2.2	5.5
7*	Partial	887	1061	6.5	12
8	Full	1039	1134	5.0	9.0
Post Weld "Hard" Condition					
Specimen ID	**Weld**	**Yield Stress MPa**	**Ultimate Strength MPa**	**Elongation %**	**Area Reduction %**
9	Partial	910	1113	9.0	23
10*	Full	1022	1178	7.0	14
11	Partial	924	1144	12.5	23
12*	Full	1110	1227	6.5	20
13	Partial	839	1127	16.0	23
14*	Full	1065	1214	5.0	18
15	Partial	850	973	6.5	10
16*	Full	967	993	1.1	2.4

* Broken at flaw

Table VII. Room Temperature Tensile Results for Weldable Waspaloy Welds

Specimen ID	Weld	Yield Stress MPa	Ultimate Strength MPa	Elongation %	Area Reduction %
1	Full	860	903	11	22
2	Partial	850	1130	12	13
3*	Full	867	1036	6.0	13
4*	Partial	824	863	4.5	6.5
5	Full	834	1090	4.5	6.5
6	Partial	899	1076	9.5	13
7*	Full	850	1066	6.0	13
8*	Partial	825	924	4.0	12
9	Full	821	994	6.5	20
10	Partial	822	1156	11	12
11	Full	887	1121	10	14
12*	Partial	796	896	4.0	6.0
13	Full	850	1163	14	18
14	Partial	810	1092	16	32
15	Full	824	1209	13	13
16	Partial	844	1108	12	22

* Broken at flaw

Mechanical Testing Results

The cast test bars are utilized to generate a mechanical property database, including both tensile and stress rupture properties. Ten standard 718Plus alloy test bars were produced. Following HIP and heat treatment, two bars were tested in each of the following conditions: room temperature tensile; 538ºC tensile; 704ºC tensile; stress rupture at 649ºC/621 MPa; and stress rupture at 704ºC/690 MPa. Tensile tests were performed in accordance with ASTM E-8 and E-21; stress rupture testing was done to ASTM E-139. Results of the mechanical testing are listed in Tables VIII and IX. Compared to the program goals listed in Table I, the 718Plus alloy casting exceeds requirements at room temperature; while both strength and ductility are marginal to goals at high temperatures. The 649ºC/621 MPa stress rupture tests show very promising results; the 704°C/ 690 MPa tests are loaded above the yield stress of the material and failed as can be expected. Additional testing will be performed at 704ºC/690 MPa to compare with internal ATI Allvac results from a previous test program.

Table VIII. 718Plus™ Alloy Castings Tensile Testing Results

Specimen ID	Temperature °C	Yield Stress MPa	Ultimate Strength MPa	Elongation %	Area Reduction %
RT-1	20	848	1124	17.5	21.5
RT-2	20	841	1152	21.5	28.0
1000- 1	538	701	934	19.5	32
1000 - 2	538	705	930	12.0	33
1200 - 1	649	667	864	16.5	24
1300 - 1	704	613	703	9.5	14
1300 - 2	704	650	767	8.5	19

Table IX. 718Plus™ Alloy Castings Stress Rupture Testing Results

Specimen ID	Temperature °C	Load MPa	Duration hours	Elongation %	Area Reduction %
SR-1300-1	704	690	0.1	5.5	17
SR-1300-2	704	690	0.08	7.5	24.5
SR-1200-1	649	621	173	3.5	18.5
SR-1200-2	649	621	349	2.5	9.5

718Plus Alloy Cast Chemistry

The re-cast chemistry of the 718Plus alloy material was also checked. Two chemistry discs were cast with the test bars from Heat WN72. The chemistry results of these two discs are listed in Table X and compared with the ingot chemistries of material provided by ATI Allvac. The cast materials show very consistent chemistries, and discrepancies between the compositions measured at PCC and those measured at ATI Allvac are likely due to the lack of appropriate standards. The chemistry of the discs will be re-measured at the ATI Allvac laboratory to get a consistent measure.

Table X. 718Plus™ Alloy Re-Cast Chemistries

Alloy	Chemistry											
	Ni	Cr	Co	Mo	W	Nb	Al	Ti	Fe	C	P	B
Heat WN71	51.4	17.83	9.03	2.72	1.02	5.39	1.79	0.79	9.47	0.029	0.006	0.003
Heat WN72	51.6	18.13	9.24	2.65	1.05	5.51	1.75	0.74	9.70	0.022	0.004	0.004
Disc 1	51.47	18.00	9.34	2.70	1.09	5.12	1.52	0.72	9.50	0.019	0.004	0.003
Disc 2	51.59	18.03	9.36	2.70	1.09	5.13	1.52	0.73	9.56	0.019	0.005	0.003

Summary

Four PCC standard molds were used in this project to study the castability and weldability of Allvac® 718Plus™ alloy and weldable Waspaloy. According to the results obtained in this study, it can be concluded that:

Alloy 718Plus exhibits similar castability as weldable Waspaloy. This is evidenced by non-concentric ring molds and hot tear molds.

Alloy 718Plus appears to be more difficult to weld than weldable Waspaloy. This is most likely related to the weld wire problems as these results are inconsistent with all weld testing conducted on wrought product. Further evaluation is required. There is no apparent difference between welding 718Plus alloy in the post-hip "soft" condition and in the post-hip "hard" condition. The results of weld mechanical testing of 718Plus alloy showed a large scatter, which is also likely related to the weld wire problems that had led to many failures at the flaws.

The mechanical properties of cast 718Plus alloy meet or exceed the expectations at room temperature; while are slightly lower than program goals at high test temperatures.

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