

OVERVIEW ON 718Plus® ASSESSMENT WITHIN “VITAL” PROJECT

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Abstract

Alloy Allvac 718Plus has been marketed by Allvac claiming better mechanical properties at temperatures where In718 has already exhausted its applicability, above the 650°C range. Allvac 718Plus also assures that it holds improved metallurgical stability at even higher temperatures, up to 700°C. In this upper range, no degradation of mechanical properties is said to happen in the new alloy. A European R&D project named VITAL dedicated part of its efforts to assess these claims and verify the improvements.

Castability and forgeability assessments were completed, together with trials on weldability of the alloy. Mechanical tests and microstructural assessments on both alloys, 718 and 718Plus, in both materials forms, cast and wrought, and two different material conditions, as-heat treated and exposed to service temperatures, were completed and direct comparisons then established.

Introduction

Alloy 718 has proven to be the most successful one in the field of aeroengine turbines. It has been applied by every company involved in the design and manufacturing of different kinds of parts within these engines, such as disks, casings, structural components and others [1, 2, 3]. Two main reasons for the success of 718 alloy are: balanced set of mechanical properties (with high levels of many of them), and ease of manufacturing (being available in all forms of material - cast, sheet, forgings - , and being also readily weldable). No other alloy has met all these targets in a more economical way.

The only alloy 718 limitation is the maximum operation temperature to which application is limited. Strengthening of the alloy is caused largely by the γ'' phase (Ni_3Nb), a metastable one which over 650°C evolves to δ phase, with the same composition but a different structure [4]. This δ phase does not have the same strengthening effect as γ'' phase has, resulting in serious weakening of the alloy.

Several other alloy systems have been tried, willing to overcome the operating temperature limitation whilst at the same time retaining the ease of manufacturing and other advantages of 718. Renè 220, RS5 or IN939 have been tested in different ways [5, 6, 7]. Allvac presented

718Plus alloy, primarily to compete with Waspaloy parts, and specifically casings, as a cheaper alternative.

ITP, VAC and CEIT were partners in this share of the European VITAL R&D program where several activities were performed to evaluate the new alloy and determine to certain extent the feasibility of using it for manufacturing aeroengine turbine structural components. These activities included production of wrought rings and cast parts from the material, welding, microstructural study after exposure to high temperatures (over 718 limits) and performing mechanical tests before and after thermal exposures.

Wrought Material

Several rings were rolled by Forgital, Italy, to assess the forgeability of 718Plus from Allvac 304.8 mm billet, see Figure 1. Chemical composition of this particular heat is given in Table 1, in weight percent. Smaller diameter pieces (from 203.2 mm down to 101.6 mm diameter) from the same heat were used for different purposes, including remelt stock to produce cast parts.



Figure 1: 304.8 mm billet used for production of forged rings at Forgital.

C	Mn	Si	Cr	Mo	Co	Ti	Al	B	Zr	Fe	P	Nb	W	V	Nickel
0.19	0.04	0.04	17.8	2.67	9.0	0.75	1.43	0.004	<0.01	9.5	0.01	5.5	1.0	0.02	Bal.

Table 1: Chemical composition of assessed material, weight percent.

Production of the rings was performed following previous experience at the forging shop with rings in 718 alloy. Rings' dimensions are shown in Table 2, and Figure 2 shows representative forgings sent for evaluation and mechanical testing. The upper one shows a cut from where material was excised for preliminary microstructural assessment before heat treatment. The same rolling temperatures, number of reheats and other values of forging parameters for these rings in 718 alloy were used. First rolling was at 1110°C, and final rolling at 1010°C. First rolling was given with 4 heats for rings 1– A and 2, and 2 heats for rings 3 and 4 – B. Final rolling was given with 3 heats for all rings. Although most of the process was performed successfully, some cracks at the corners of the rings appeared during rolling, as can be seen in Figure 3. These indicate that the manufacturing process needs to be modified, and that those 718 alloy forging parameters cannot be directly applied for the new 718Plus if a totally sound product is expected to be obtained from the manufacturing process.

Ring identification no.	Start weight (kg)	Finish Weight (kg)	Finish Sizes (mm)
1 - A	250	237	897 × 1001 × 190
2	250	227	903 × 996 × 190
3	225	208	917 × 995 × 220
4 - B	225	211	920 × 1000 × 222

Table 2: Dimensions of produced rings.

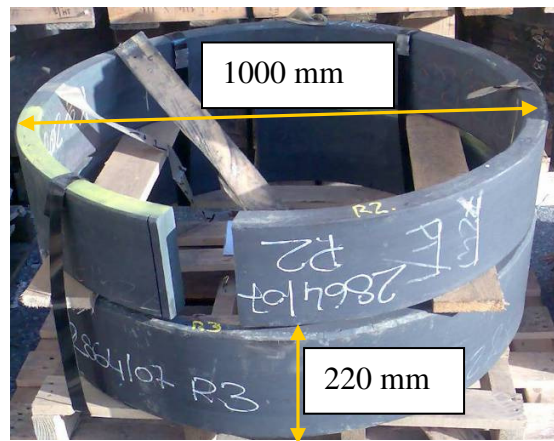


Figure 2: Rings 2 and 3 after forge at Forgital.



Figure 3: Cracks at corners of rings forged to final shape.

The different geometries and manufacturing routes of the rings resulted in quite different microstructures. The grain size of rings 1 - A and 2 (thicker, shorter ones) was ASTM8 while the grain size of rings 3 and 4 - B (thinner, taller ones) was ASTM5. Rings 3 and 4 - B had an additional reheat at 1010°C, which resulted in this larger grain size. At the same time, a lower amount of δ phase was also noticed. Figure 4 shows these differences.

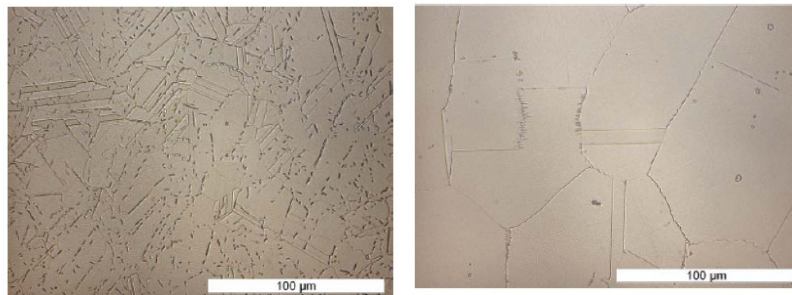


Figure 4: Microstructure of as rolled rings, representing rings (1-A and 2) ASTM8 grain size, δ phase (left), and rings (3 and 4-B) ASTM5 grain size, little δ (right).

This microstructure evaluation after rolling was used for selection of optimized heat treatment. It has been largely recognized by Allvac that the amount of δ phase present in the alloy needs to be carefully balanced to produce the desired combination of mechanical properties [8]. Following this assessment, an additional pre-solution heat treatment was applied to thinner rings, which consisted in a 870°C heating for 16 hours. This decision was based on the fact that the amount of δ phase was so low that the material would be notch sensitive. The same heat treatment for properties was applied afterwards to both sets of rings, with the following conditions:

- Solution annealing at 970°C during 1 hour, water cooling.
- Ageing at 788°C during 8 hours, air cool to 704°C, maintain 8 hours, air cool.

Figure 5 shows the resulting microstructure after complete heat treatment of both sets of rings.

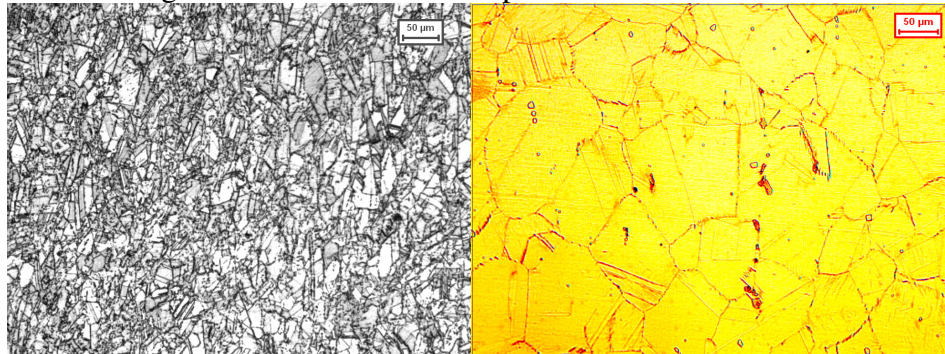


Figure 5: Micrographs of heat treated rolled rings thicker rings (1-A and 2) ASTM8 grain size, δ phase (left), and thinner rings (3 and 4-B) ASTM5 grain size, no δ , (right).

Heat treated rings were subsequently investigated, with microstructural assessment and performance of mechanical tests, as described briefly afterwards in detail elsewhere [9].

Cast Material

Casting trials were completed at PCB, Precicast Bilbao, Spain, to assess the feasibility of producing cast parts from this alloy. Trials included production of Separately Cast Test Bars, stair shaped cast plates for repair welding evaluation [10], hollow cylinders for mechanical testing, and a demonstration cast part, designed in a previous European R&D project [3]. This particular geometry includes different vane thicknesses, fillet radii, lugs and various local features that resemble usual features in structural components of aeroengine turbines. Figure 6 shows some of these produced parts. Table 3 provides dimensions of these castings.



Figure 6: Stair shaped cast plates(left); hollow cylinders (centre); democast (right).

Stair shaped cast plates	400 mm long × 400 mm wide × 9, 15, 30 mm thick.
Hollow cylinders	285 mm OD – 225 mm ID × 120 mm high.
Democast	550 mm OD × 170 mm high.

Table 3: Dimensions of produced castings.

It must be borne in mind that the intention of this evaluation (moreover in this case of the cast form) was just to make a preliminary assessment of alloy castability. The material was coming from the same heat from where billet for production of the forged rings (the chemistry was thus also the one given in Table 1). Therefore, chemical composition was not optimized for castings.

Trials completed at PCB with these different geometries indicated that casting parameters to be used for the alloy could be the same that those used for regular 718. Production of rings and stairshaped plates was satisfactory (dimensional accuracy wasn't a goal), and the production of the democast was also successful, given the complexity of the part and the lack of a development process, that would typically be required for producing this type of components.

Thickness as low as 1,4 mm were placed on areas of the democast, but no misruns were detected, so the alloy has proved not to be prone to rapid solidification which would inhibit fill of thin sections. Some cracks were detected in thin areas located away from the feeding system between other thicker areas. It seems that the faster cooling and solidification of these areas has been followed by the stresses imposed by the adjacent thicker areas due to shrinkage or contraction during solidification (lasting longer in those thicker areas). The lower load resistance capacity of the thin areas has then resulted in cracking by a hot-tearing mechanism, see Figure 7. It was considered that the gating system was too heavy for the part, but subsequent development of the casting process would be capable of achieving much better results.

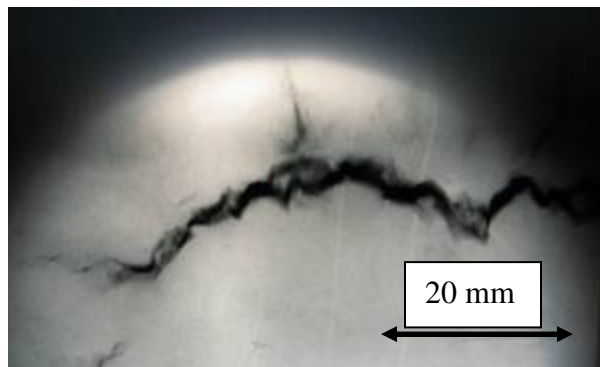


Figure 7: Morphology of cracks at thin areas of demonstration casting, as seen on X-ray plates.

In addition to the weld repair assessment performed on cast plates [10], some weld repair trials were also successfully completed on the democast, covering different features and thicknesses, see Figure 8. These were made by TIG welding using 1.2 mm diameter filler material supplied by Allvac. The part was welded in the as-HIPed condition, prior to solution heat treat to demonstrate the feasibility of completing this kind of operation, typically required for manufacture of complex castings.

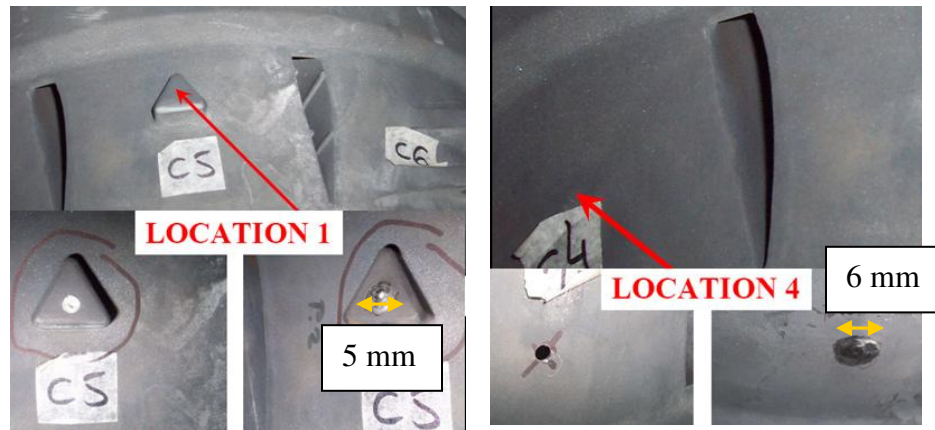


Figure 8: Weld repair trials performed on democast.

The hollow cylinders were used for selection of heat treatment parameters, and evaluation of mechanical properties. The former investigated the application or not of homogenisation before HIP on the material, and the effect of different solution heat treatments on microstructure and thus mechanical properties [11]. Finally, the cast ring for mechanical tests received a heat treatment consisting of HIP at 1120°C, 103 MPa of Argon pressure for 4 hours, then solution at 982°C, fan air cooled, and aged at 788°C for 8 hours, air cool to 704°C, maintain 8 hours, air cool. This heat treat was also applied to the demonstration casting. The mechanical properties were assessed in the heat treated condition and also after thermal exposure, as explained briefly in this paper and in detail elsewhere [9].

Weldability

Initial assessment of 718Plus weldability was performed through Varestraint and TransVarestraint testing on sheet material. These two different tests are intended to evaluate how prone the alloy is to HAZ cracking and solidification cracking, respectively. By imposing various strains during the welding by bending test samples at the same time, it is possible to assess the propensity for cracking. This propensity is usually measured as the total amount of cracking that can be measured after weld operations performed in fixtures such as those depicted in Figure 9. Details on these results are given elsewhere [12], but generally indicate that weldability is comparable to that of regular 718 and in any case much better than that of Waspaloy.

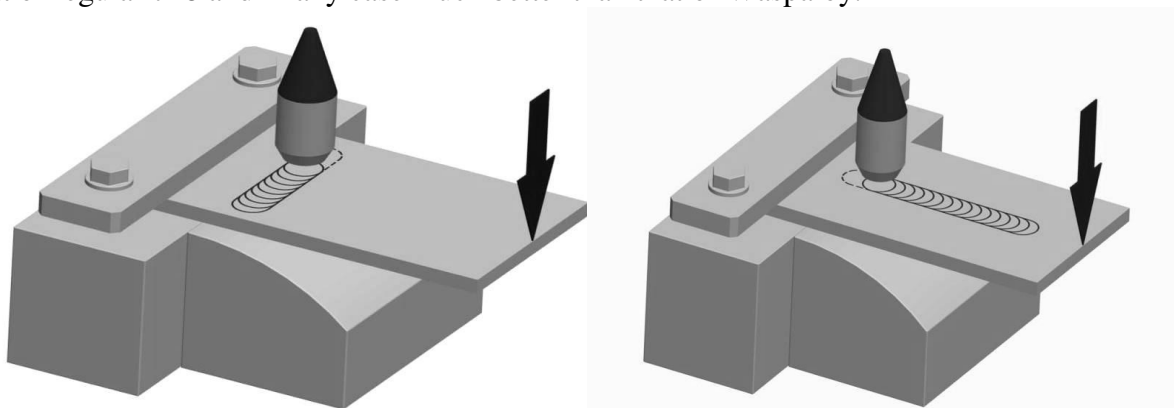


Figure 9: Schematic overview of TransVarestraint (left) and Varestraint (right) testing methods.

It is always arguable how the measured total crack length (TCL) can be practically utilized but by comparing with other alloys of interest a rating can still be made to assess “weldability”. Comparison by this testing was made with regular 718 alloy and Waspaloy, Figure 10. It is obvious that there is considerable scatter but still it is evident that Allvac 718Plus comes out at par with 718 alloy, which is known for its good weldability. In this testing Waspaloy is least prone to cracking which may be surprising since its weldability is usually considered as poor. However, this anomaly can be understood due to the post-weld heat treatment response in Waspaloy, which causes strain age cracking in Waspaloy. This is not likely in either 718 alloy or Allvac 718Plus due to the slow sluggish hardening response in these two latter alloys.

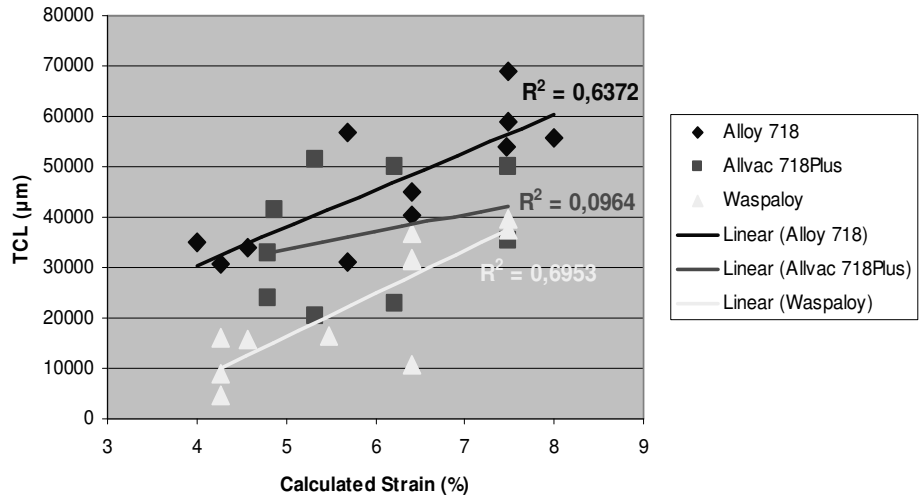


Figure 10: Vareststraint comparative testing results.

Other trials were also completed on the stair shaped castings, where influence of the different homogenization temperatures applied to the castings was studied, and on the forged rings. The latter ones were welded using EB, while the former ones were performed by TIG welding, usual repair method for castings. EB-weld tests were performed on the wrought rings with excellent results indicating that the Allvac 718Plus alloy is well suited for joining circular large sections together [13]. Of special interest was the observation that microfissures seemed to heal due to a good backfilling by the eutectics involved (MC and Laves).

To understand the potential of Allvac 718Plus for casting, weld repairability was assessed on the stair case shaped platecastings in which both thin and thick cross-sections could be evaluated, Figure 11.

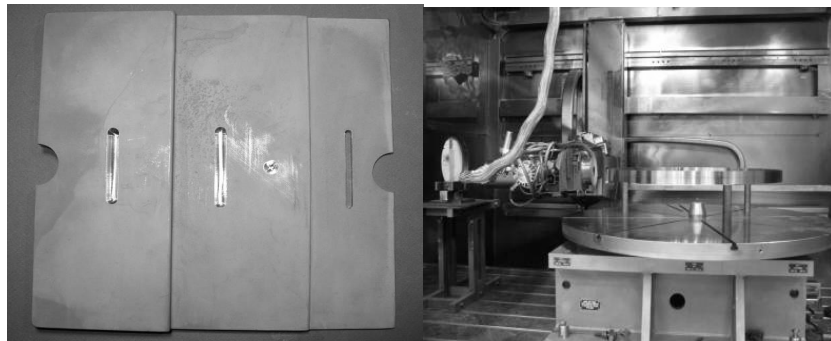


Figure 11. Weld repair setup cast 718Plus (left), and electron beam welding setup forged 718Plus (right).

Results indicated that high temperature homogenization heat treatment such as 1200°C decreases the weldability whereas homogenization treatments at lower temperature such as 1125°C is beneficial for weld repair of cast 718Plus [9], Figure 12. The benefit of the latter one is ascribed to enhancement of the ability of backfilling since more eutectic phase constituents are present within the microstructure.

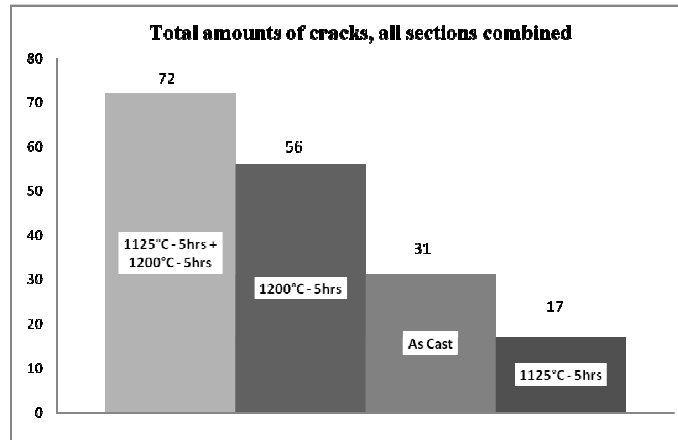


Figure 12. Total amount of cracking for each specific condition when all sections are combined is represented.

The EB welding trials were performed on three different thicknesses (6 mm, 12 mm and 20 mm) varying weld parameters such as welding speed, accelerating voltage and current [13]. Although a wide range of parameters were used, no cracks were found. Metallographic examination revealed that also here backfilling had an important role. It seemed like the δ phase promotes a Laves phase transformation through constitutional liquation which improves in healing cracks, Figure 13.

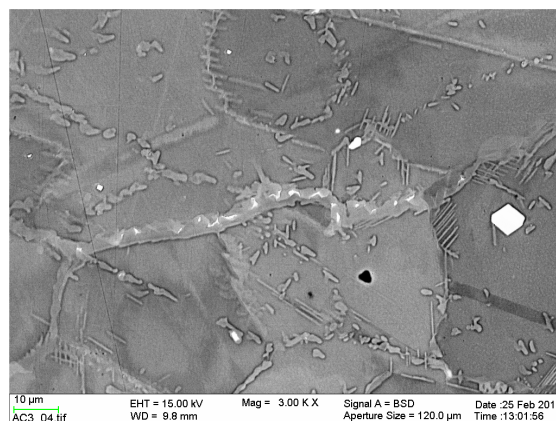


Figure 13. Backfilled crack during EB welding of forged 718Plus.

Exposure to High Temperatures

As mentioned, one of the main objectives of the "VITAL" project was to establish the improvement in operating temperature capabilities of the new alloy over the regular 718. To assess this, both rolled rings and cast rings were exposed to a number of hours at high

temperatures that would certainly cause a degradation of 718 alloy mechanical properties. The selected conditions of thermal exposure were 140 hours at 700°C, and then 460 hours at 675°C. These conditions were chosen as it is known that exposure at lower temperatures (around 650°C) would require much longer exposures to significantly affect mechanical properties of the material [14].

Samples of regular wrought 718 material were taken from available ring-rolled parts, with the chemical composition given in Table 4. The material had a grain size of about ASTM9, comparable to the thicker rings produced at Forgital. A cast ring of the same dimensions of the previous 718Plus cast rings was produced at PCB. Chemical composition is given in Table 4.

Part	C	Mn	Si	Cr	Mo	Ti	Al	B	Zr	Fe	P	Nb	Nickel
Rolled ring	0.025	0.05	0.06	18.0	2.93	1.00	0.49	0.004	--	18.05	0.008	5.2	Bal.
Cast ring	0.06	0.02	0.06	19.3	3.01	1.01	0.54	0.004	<0.01	17.72	0.004	5.1	Bal.

Table 4: Chemical composition of wrought and cast 718 rings, in weight percent.

Microstructural characterization was performed here, including determination of δ phase volumetric fraction by image analysis and application of ASTM E562-89 standard. As expected, percentages of δ phase increased significantly in regular 718 alloy, with values increasing from around 8% in the heat treated condition to over 17% in the exposed condition. Grain size, however, did not change with this exposure. This analysis was not performed for 718Plus, as mechanical properties were not degraded. Figure 14 shows the difference in δ precipitation for wrought alloy 718. It was observed that once the amount of precipitation is significant, the δ precipitation occurs not only along the grain boundaries, but also within the grains.

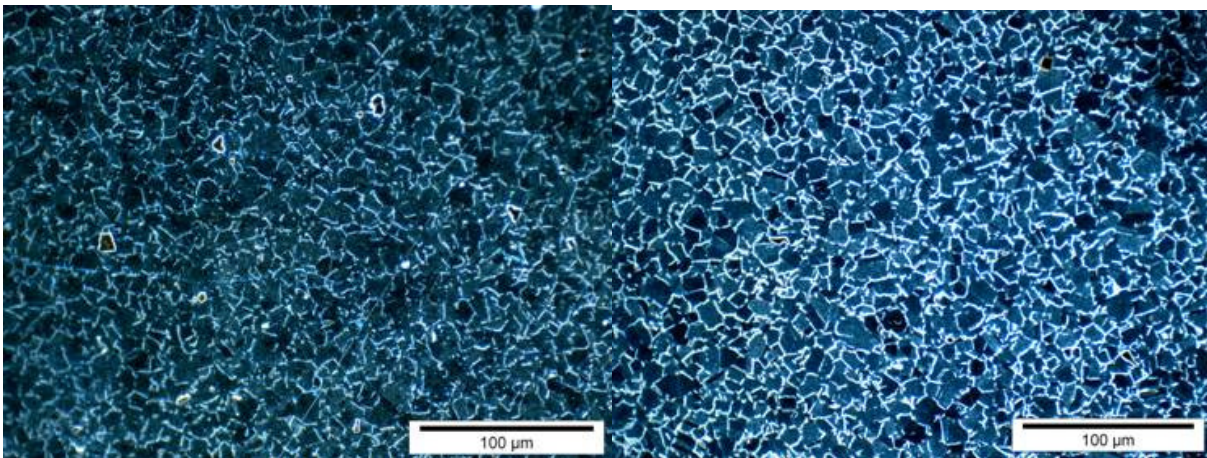


Figure 14: Micrographs of δ precipitation on wrought alloy 718 as heat treated (left), and after exposure at 700°C for 140 hours plus 675°C for another additional 460 hours (right).

For wrought 718Plus alloy, analyses were also made on both fine grain and coarse grain materials, and also showed the noticeable increase in δ phase precipitation, see Figure 15 and compare with Figure 5, for material in the as-heat treated condition.

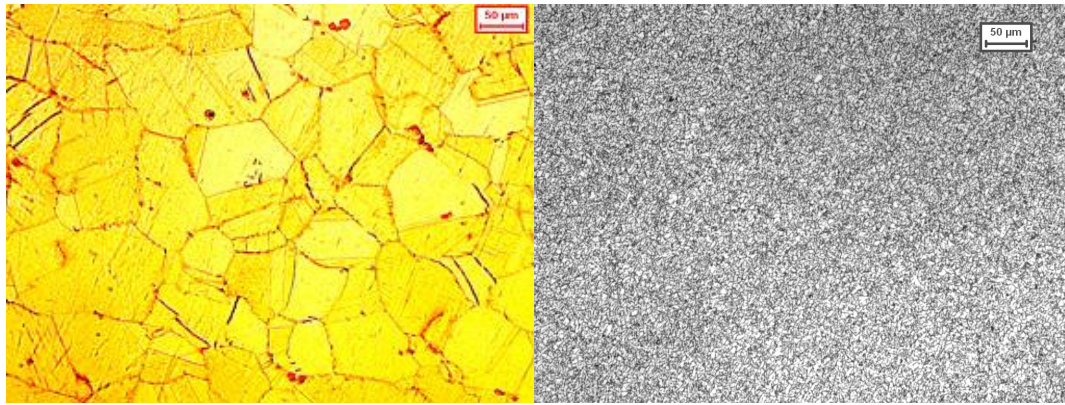


Figure 15: Micros of heat treated and exposed rolled rings thicker rings (1-A and 2) ASTM8 grain size, δ phase, (left), and thinner rings (3 and 4-B) ASTM5 grain size, no δ , (right).

For the cast material, however, the influence of exposure in the microstructural condition of the material was not so significant. This is observed through the microstructural assessment of the material in the different heat treatment conditions: as-cast, homogenised (if this was applied), HIPed, solutioned, aged and, finally, exposed. The detected changes (dissolution of Nb segregations, and precipitation of δ phase) are more pronounced in the first steps, at higher temperatures, than during the final exposure. Figure 16 shows an example of this, with details given elsewhere [11].

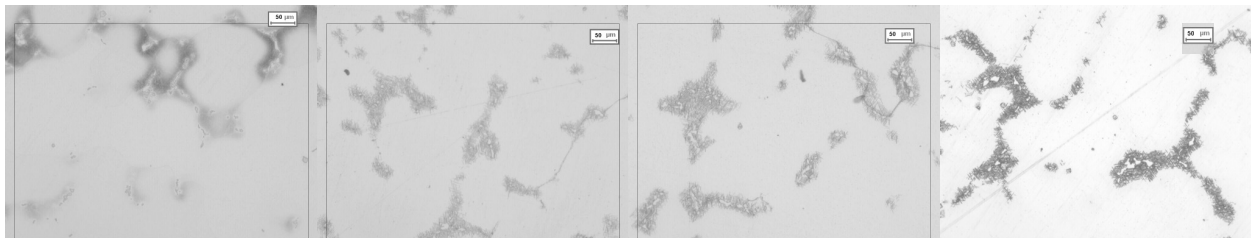


Figure 16: Evolution of cast 718Plus rings microstructures through different conditions, (left to right):

Homogenized at 1095°C, 1 hour and HIPed at 1120°C, 4 hours; previous after solutioned at 982°C, 1 hour; previous after aged at 788°C during 8 hours, air cool to 704°C, maintain 8 hours, air cool; previous after exposure to VITAL conditions.

Mechanical Tests

A mechanical test plan was designed to test the different materials, forms and conditions available after completing all the previous activities. This plan originally included the alloys 718 versus 718Plus, times the two material forms (wrought versus cast), times the two material conditions (as-heat treated versus exposed), which made 8 material conditions to be tested. Each of the partners in the project took care of a particular kind of mechanical test, CEIT performing or subcontracting tensile, ITP completing LCF, and VAC doing the crack growth and stress rupture. This was afterwards modified, as it seemed more interesting to test the two different microstructural conditions resulting in the rolled rings from the different forging routes than the cast form of the material. As the casting composition would be modified once the chemical

composition studies and modifications for castability were completed at Allvac, it didn't make sense to dedicate much effort to these tests. Over 120 mechanical tests were completed in total.

Tensile properties - Castings

It has to be mentioned that results on casting forms of the alloys brought a couple of surprises. The regular 718 not only did not degrade its mechanical properties after exposure, but it did even improve them. This is contrary to all literature published up to date, though it is true that this literature rarely refers to cast material, but is mostly dedicated to the wrought form. This increase in yield strength for 718 after the exposure to high temperature can be noticed in Figure 17. It is consistent through the testing temperatures. A possible explanation for this is that the Nb retained in segregations that appeared in the rather thick section of the rings from where the samples were excised was freed through diffusion during exposure to form additional strengthening precipitates. However, this effect is not seen in 718Plus, which would make the explanation weak. But it has to be considered also that γ'' is not recognised as the main strengthening phase in 718Plus, so diffusion of Nb wouldn't strengthen it much further.

It is also surprising to see scarce, if any, advantage of 718Plus from regular 718, either before or after exposure. This might demonstrate that the chemical composition optimisation was still needed.

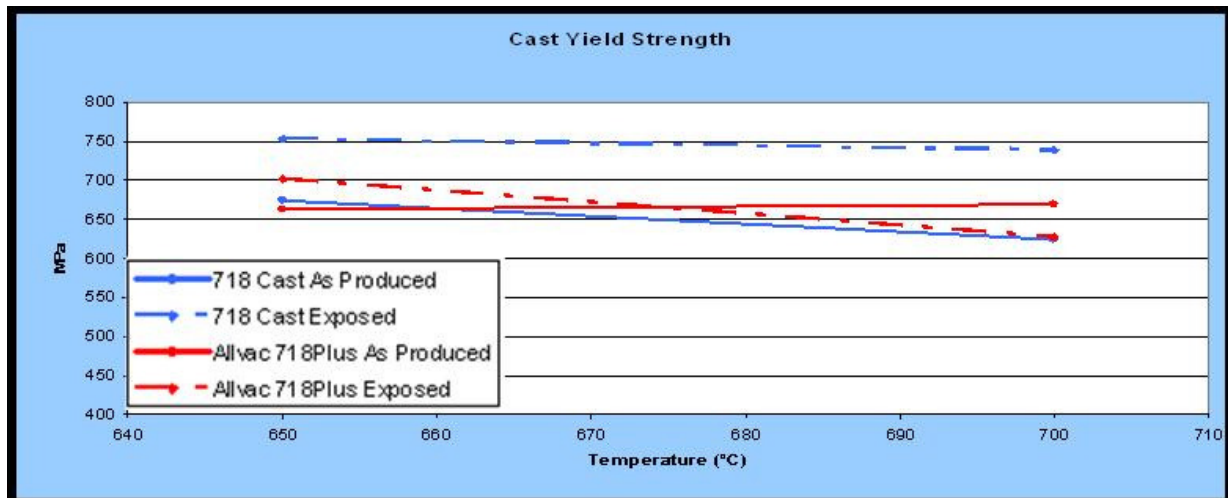


Figure 17: Yield strength of cast form of 718 and 718Plus at different temperatures, before and after exposure.

Tensile properties – Wrought Material

Degradation in mechanical properties of regular 718 is clearly noticeable in Figure 18. Also note that the finer grain size of 718Plus presents better values than the coarser one. There is still another fact which will be mentioned afterwards, which is the larger response of the coarse grain 718Plus to the exposure, compared to the fine grain one. Whilst the fine grain material stays pretty stable, the coarser structure reacts positively to this exposure, improving yield strengths.

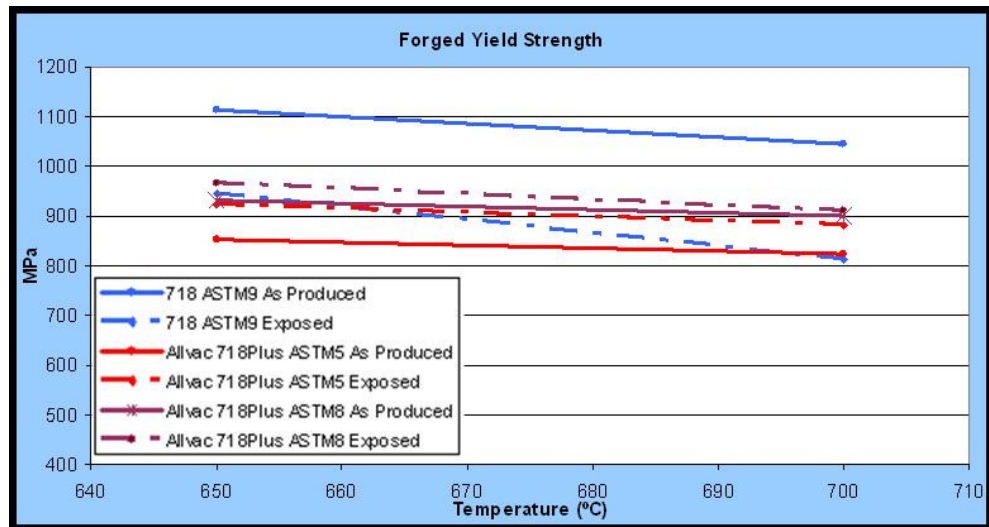


Figure 18: Yield strength of wrought form of 718 and 718Plus at different temperatures, before and after exposure.

The higher yield strengths of regular 718 compared with 718Plus are partially attributed to the finer grain size of the regular 718 rings. The regular 718 ring has finer grain size (ASTM9, instead of ASTM8 for 718Plus ring), which, together with the non-optimal manufacturing route (and thus non-optimal microstructure) of the 718Plus rings, explains the advantage that can still be observed for the regular 718 rings. This higher strength of regular 718 at lower temperatures has also been noticed in other studies and publications from Allvac.

Stress rupture properties

Cast materials were not tested in this case. Stress rupture tests on smooth cylindrical specimens showed that both the time to fracture and elongation are significantly higher in forged 718Plus than those required by specification AMS5663 for 718, at 689 MPa and 649°C. Long time exposure, however, reduces both elongation and time to fracture but the values are still above the 718 specification. Even though the elongation decreases, so does the average creep rate (if approximated as elongation divided by time to fracture), indicating an improvement in the resistance to creep deformation with exposure.

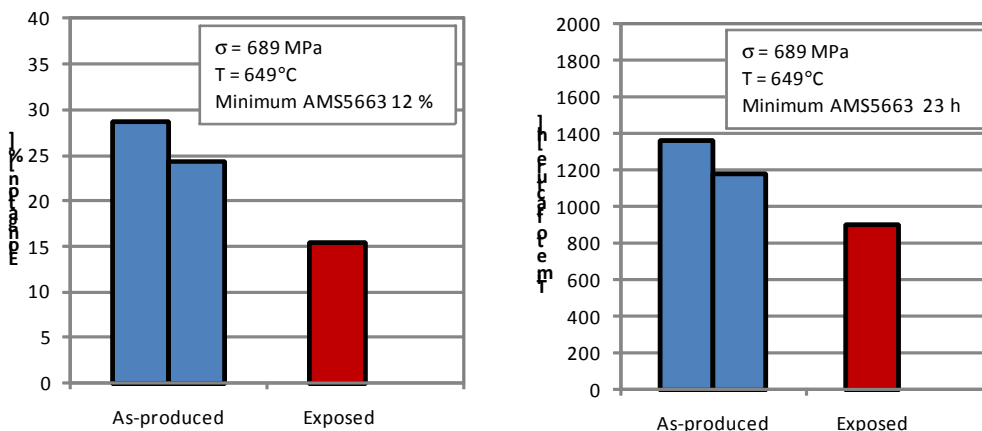


Figure 19: Stress Rupture of wrought form of 718Plus, before and after exposure.

Fatigue properties

For these tests, the geometry of tested samples was the one shown in Figure 20. All LCF samples were produced using low stress grinding for final surface finish.

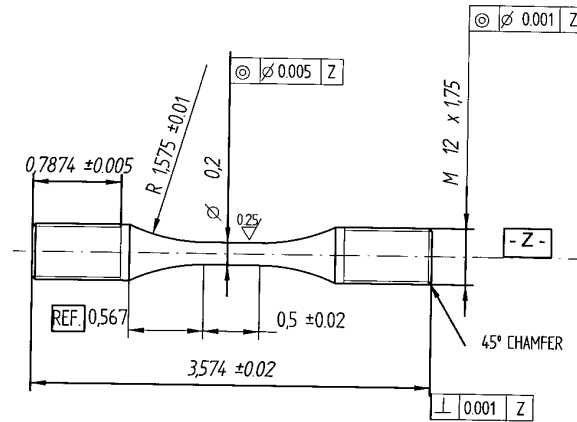


Figure 20: LCF test samples geometry.

Regarding LCF, wrought 718Plus proved to be more resistant to thermal degradation than baseline 718 alloy. As was already reported in the tensile discussion, the 718 properties do significantly degrade when exposed to high temperature; this fact is confirmed and again supported here. What is now even more easily noticed is the improvement that the coarse grain 718Plus material has achieved after the exposure. This was more noticeable in tests performed at high temperatures, and is again consistent with previous results in tensile tests. A possible explanation follows. Given that, as mentioned in the “wrought material” section above, these particular pieces of material had received an extra heat during rolling operation which resulted in solution of the δ phase, the larger grain size material had only the capability to make the δ precipitate during the exposure of the material. This hypothesis does also consider that the coarser grain material offers a smaller amount of grain boundaries, where the δ phase preferably precipitates. The smaller grain size material had a much larger grain boundary surface, enough to precipitate all δ during initial heat treatment. If this hypothesis is considered, together with previous information from the “wrought material” section above, both together lead to the idea of a material more sensible to manufacturing conditions than regular 718 alloy.

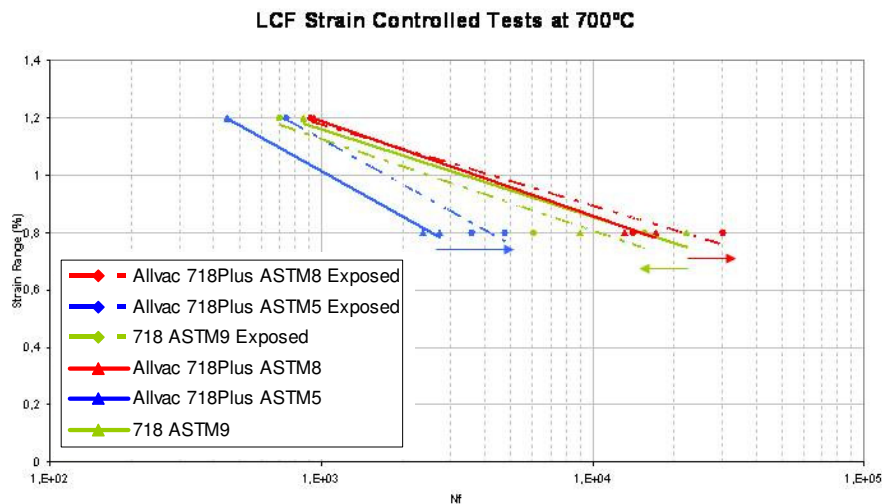


Figure 21: Low Cycle Fatigue properties of wrought form of 718 and 718Plus at 700°C, before and after exposure.

Crack growth properties

Cast materials were not tested in this case. Crack growth tests were also performed at different temperatures and the results are reported in more detail elsewhere [15]. These tests did also include different conditions, with or without hold time being considered, from none to 90 seconds, to over six hours. 718Plus showed a behaviour dependant upon the testing temperature, with no hold time effect at 450°C, but with 10 times higher rates at 700°C when 90 seconds hold time is included. This effect grows exponentially when the hold time is increased to six hours. Comparison with 718 results show that, for the 90 seconds hold time, values of crack growth rate for 718Plus at 700°C are similar to those of 718 at 600°C. In other words, there is a 100°C advantage of 718Plus over regular 718, see Figure 22. After long time exposure, the resistance to hold-time fatigue crack growth decreased, whereas the cyclic crack growth rate was unaffected. The mechanism behind the reduced hold time crack growth resistance in the exposed condition is not clear at present, but the explanation can be assumed to be related to changes in grain boundary δ phase structure and development of the hardening precipitates. Hold time crack growth behaviour is also generally inversely dependent on the stress relaxation properties of the material. The crack growth tests were performed on coarse grained material, and the improved tensile properties after exposure, mentioned earlier, could be expected to reduce also the primary creep rate which would be detrimental to the hold time properties. This is consistent with the observed reduction in average creep rate above.

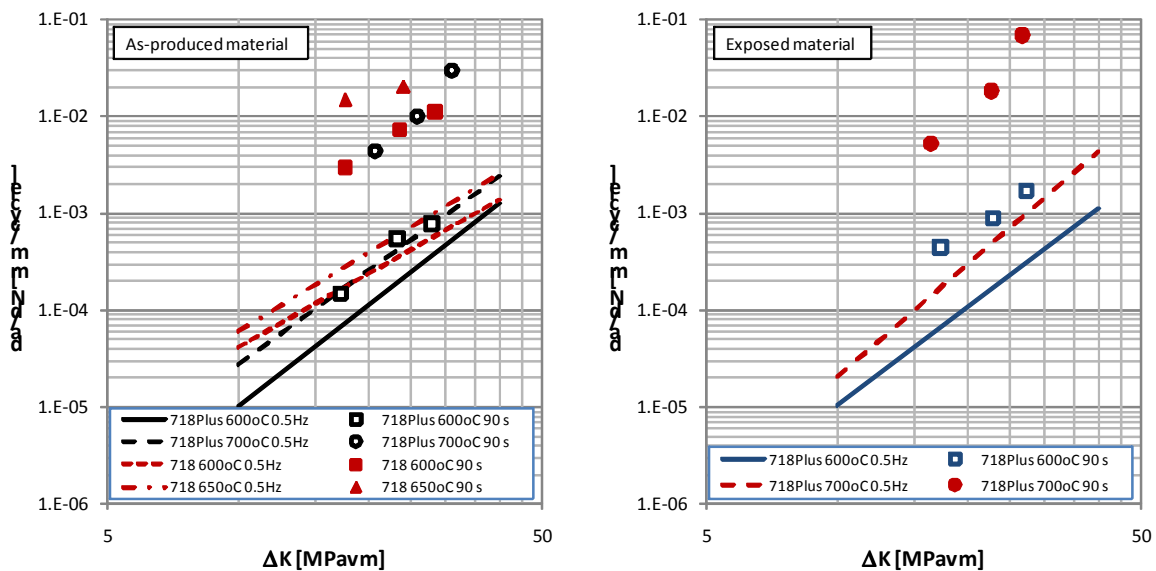


Figure 22: Crack Growth Rate tests of wrought form of 718 and 718Plus before exposure (left), and after exposure (right), including 90 seconds hold times.

Conclusions

1. It is possible to manufacture parts in 718Plus alloy in wrought and cast forms, and also to weld the parts in this alloy. However, some cautions should be taken, as it is not as easy to manufacture these parts as it is from 718; some modifications must be made in manufacturing parameters. However, the alloy is much easier to process than Waspaloy.

2. 718Plus is quite sensitive to manufacturing parameters, and heat treatment should be adjusted to resulting manufacturing microstructures after shaping.
3. Advantage of 718Plus over 718 in operating temperature capabilities is demonstrated and has been quantified at about 100°C. Stability in the range where regular 718 shows degradation is also proven.
4. Cast 718 mechanical properties improve after exposure at times and temperatures where wrought form of the same alloy starts to degrade.

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