**Superalloys 718, 625, 706 and Derivatives 2005** *Edited by E.A. Loria*
*TMS (The Minerals, Metals & Materials Society), 2005*

# STRUCTURE AND PROPERTY COMPARISON OF ALLVAC® 718PLUS™ ALLOY AND WASPALOY FORGINGS

Ian Dempster[1], Wei-Di Cao[2], Richard Kennedy[2], Betsy Bond[2], Jose Aurrecoechea[3], and Mark Lipschutz[3]

[1] Wyman-Gordon Houston Forgings, 10825 Telge Road, Houston, TX 77095, USA
[2] ATI Allvac, 2020 Ashcraft Avenue, Monroe, NC 28110, USA
[3] Solar Turbines Incorporated, 2200 Pacific Highway, San Diego, CA 92186, USA

Keywords: Allvac® 718Plus™ , Waspaloy, Mechanical Properties, Thermomechanical Processing, Heat Treatment

## Abstract

Alloy 718 has seen extensive use for many years due to its excellent mechanical properties, good processing characteristics, and relatively low cost. Numerous attempts have been made to develop a 718-type alloy with temperature capabilities higher than alloy 718. One of the most promising alloys to emerge from these efforts is Allvac® 718Plus™ Alloy. Interest in alloy 718Plus has grown after initial testing showed a 55ºC temperature capability improvement over alloy 718, mechanical properties comparable to waspaloy, and processing behavior similar to alloy 718.

A comparison between the structure and properties of alloy 718Plus and waspaloy was performed on pancake forgings produced using an open-die process. The forgings were subjected to grain flow evaluations and subsequently heat-treated. The tensile, creep, and stress rupture properties of the pancake forgings were determined and related to their respective structures.

## Introduction

Industrial gas turbines users demand high efficiency, superb performance, low emissions, and excellent durability from their equipment, along with an attractive life cycle cost. Materials of construction, particularly those of turbine hot section components, play a key role in meeting these demands. The increasingly stringent operating requirements of turbine blades, disks, and stationary components such as nozzle vanes and seal rings have stimulated alloy development activities for decades.

Industrial gas turbine disk material evolution reflects the pursuit of improved thermo-mechanical processing behavior and properties. Early industrial gas turbines relied on alloys such as A-286 and alloy 901, but increasing operating temperatures and stresses led to the utilization of more capable alloys such as alloy 718, waspaloy and alloy 706.

The extensive use of alloy 718 in industrial gas turbines is due to its attractive properties and excellent processing behavior. However, the upper use temperature of alloy 718 is limited to 650°C. The coherent γ” phase primarily responsible for alloy 718’s strength is thermo-dynamically unstable at elevated temperatures, transforming to δ phase. This transformation is accompanied by a significant deterioration in mechanical properties.

Gamma prime strengthened alloys such as waspaloy, René 41, and U-720 have been used in industrial gas turbine disk applications where operating requirements dictate a more capable alloy than alloy 718. However, these stronger alloys are also more costly and difficult to process. Therefore, the development of an alloy combining the processing ease of alloy 718 with the enhanced properties of more advanced disk alloys has long been an objective.

Most of the numerous efforts to surpass the high temperature capability of alloy 718 have been aimed at increasing the strengthening effect and thermal stability of the γ" phase in an alloy, like alloy 718, strengthened primarily by γ" [1, 2, 3, 4, 5, 6, 7, 8, 9]. A second approach consisted of developing a γ" strengthened alloy with better processing behavior, enhanced properties, and lower cost than γ' strengthened alloys, as exemplified by René 220 [10] and GE Alloy 991 [11]. A third approach involved the addition of trace elements to alloy 718 to improve properties, without compromising its processing characteristics [12, 13, 14]. Unfortunately, none of the newly developed alloys have achieved the desired capability improvements over alloy 718 while maintaining the ease of processing characteristic of alloy 718.

## Objective

Experience in processing of alloy 718Plus for disc applications is limited, therefore this program was initiated to evaluate the effects of thermomechanical processing and heat treatment on mechanical properties and microstructure that may be applied to manufacture of large alloy 718Plus forgings. The formability of alloy 718Plus will also be evaluated within the limited scope of the program.

## Experimental Program

All the forgings in this study were manufactured on the Wyman Gordon 2500 Ton Advanced Product Development press using flat dies and a reduction ratio of 3:1. Allvac supplied the alloy 718Plus and waspaloy 200mm diameter billet used in the program. Both materials were produced from 500mm diameter VIM+VAR ingot, upset and drawn to an intermediate preform diameter and finish forged by a GFM. Typical chemical analysis alloy 718Plus and waspaloy are given in below.

| Alloy | C | Cr | Mo | W | Co | Fe | Ni | Nb | Ti | Al | P | B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alloy 718Plus | 0.025 | 18 | 2.7 | 1.0 | 9.0 | 10.0 | Bal | 5.4 | 0.7 | 1.45 | 0.014 | 0.004 |
| Waspaloy | 0.035 | 19.4 | 4.3 | 0 | 13.5 | 0 | Bal | 0 | 3.0 | 1.3 | 0.006 | 0.006 |

The program was conducted in two phases. The first phase evaluated the effects of forging temperature, solution temperature and ageing time on structure and properties. In the second phase, the study was restricted to the solution treatment conditions for alloy 718Plus and included a trial with a waspaloy forging.

Three alloy 718Plus forgings were produced for the initial phase of the program using temperatures in the range 996-1024ºC. The 200mm diameter billet multiples were upset with a 3:1 reduction to yield a 60mm thick forging. Each forging was halved, solution treated at temperatures of 955ºC or 982ºC, and oil quenched. A 857°C for 8 hrs presolution thermal cycle was applied before raising the material to the solution temperature.

Aging of alloy 718Plus is similar to alloy 718 but at higher temperatures (dual age cycles at 788°C and 650°C, with an intermediate cool at about 55°C/hour, followed by an air cool). To complete the test matrix, quarter forgings were aged for 2 or 8 hours at the 788ºC temperature of the age cycle.

In the second phase of the program a forging temperature of 1038ºC was selected for the alloy 718Plus forgings. The forgings were produced from 200mm diameter billet with a 3:1 reduction to a final thickness of 100mm. The forgings were halved and heat treated. Further evaluation of the solution temperature was also performed in this phase of the program. A presolution heating cycle was used on three of the forging sections before raising to the solution treatment temperatures of 955, 968 and 982ºC and oil quenching. One section was heated directly to 955ºC and oil quenched. All forging were aged using the 788ºC / 650ºC dual age cycle.

A waspaloy forging, supersolvus forged at 1071ºC, was produced from 206mm diameter billet with a 3:1 reduction ratio to a final thickness of 100mm. After sectioning into two pieces, one section was heat treated by solution treating at 1020ºC oil quenched, stabilized at 843ºC and aged at 760ºC. The waspaloy test results are compared with the alloy 718Plus phase 2 forgings.

Mechanical property testing for both phases of the program involved room temperature tensile, elevated temperature tensile, stress rupture and creep testing. All elevated temperature tests were performed at 704ºC. Stress rupture and creep specimens were run at 551Mpa and 483Mpa stress levels respectively

For the first phase of the program, two test specimens of each type were removed in both the radial and tangential orientations from each of the fully processed quarter forgings. All specimens were taken from the middle third of the forging thickness and the midradius.

For the second phase, three room temperature and elevated temperature tensile test specimens were taken in the radial direction and three creep and three stress rupture tests were taken in the tangential direction. All specimens were taken from the middle of the forging thickness and in the mid radius location from both alloy 718Plus and waspaloy forging sections.

## Results and Discussion

In initiating this program, there was very little data on the forgeability of alloy 718Plus, although it had been formed by ring rolling successfully as part of the alloy development program. Forging trials conducted by Allvac, not reported here, showed no evidence of forging cracks and suggesting alloy 718Plus has good formability.

Over the temperature range 982 to 1038ºC, and reduction ratio of 3:1 used in both phases of the program, no evidence of surface cracking or tearing was observed in the alloy 718Plus forgings. The good surface condition of the forgings suggests that alloy 718Plus is not crack sensitive within the range of conditions used in this study.

While it is recognized in the industry that waspaloy has formability issues and is crack sensitive during forging, the waspaloy forging produced as part of this trial did not show any evidence of fracture. This indicates that the upset forging is not a severe test of the forgeability of alloy 718Plus and more evaluations will be necessary to explore the limits of hot workability.

Both the alloy 718Plus and waspaloy forgings show deformed and partially recrystallized grains in the area of the die contact faces. This extends from the forging surface to a depth of approximately of 5-10mm. Figures 1 and 2 show the microstructure at mid-radius location 6mm from the forge surface and at mid thickness for a fully heat treated alloy 718Plus forging formed at

1038ºC. The depth of the unrecrystallized/partially recrystallized material will have an impact on the forging envelope and hence manufacturing cost for a component.


Figure 1. 6mm from forging surface

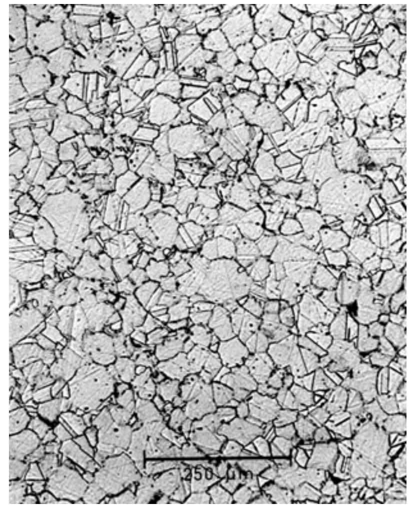


Figure 2. Forging mid thickness

The uniform, recrystallized grain size in the forgings was a function of the forge temperature and ranged from an average of ASTM 9 ALA 8 for the 996ºC, ASTM 8 ALA 7 for 1010ºC, ASTM 7 ALA 6 1024ºC and ASTM 6 ALA 5 for the supersolvus 1038ºC forging, shown in Figure 3.

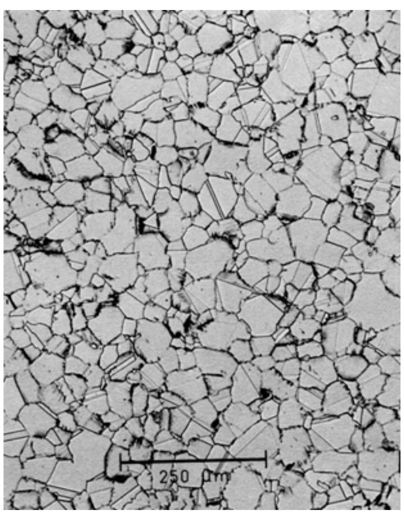


Figure 3. Alloy 718™ Plus Forged 1038ºC

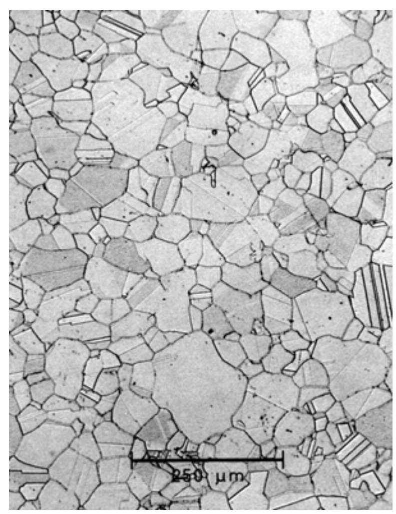


Figure 4. Waspaloy Forged 1071ºC

Waspaloy upset at 1071ºC had an average ASTM 5 ALA 4 microstructure, figure 4, and the similarity in grain size between the alloy 718Plus and waspaloy forgings eliminated that grain size was not an issue in making a comparison of the mechanical properties.

Balancing the mechanical properties was the principal consideration for selecting the heat treatment conditions. The previous development program indicated that, like alloy 718 and alloy 706, alloy 718Plus may be susceptible to low notch ductility. Therefore the heat treatment had to balance achieving good tensile properties and minimizing the risk of stress rupture notch ductility failure.

The heat treatment was designed to precipitate delta phase on the grain boundaries in order to reduce susceptibility for notch failures. This was accomplished by using the presolution heating cycle at an intermediate temperature and limiting the time at solution temperature. The solution temperature range was selected to retain sufficient Nb, Al and Ti in solution for precipitation of gamma prime and gamma double prime during the age cycle.

Tables I and II show the ambient and elevated temperature tensile properties respectively for alloy 718Plus for different forging and solution temperatures. The data shown are the average of two tests for each forge and solution treatment condition. In general, room temperature strength appears to be negatively impacted at the highest forge temperature with an attendant pick up in ductility whereas the higher solution temperature promotes improved strength levels. The elevated temperature properties do not appear to be sensitive to the forge temperature, though the same effect of solution temperature is observed.

Table I. Effect of Forge and Solution Temperature on Average RT Tensile Properties

| Average Room Temperature Tensile Properties | | | | | | |
|---|---|---|---|---|---|---|
| Forge Temp. ºC | Solution Temp. ºC | Tensile Stress MPa | Yield Stress MPa | %Elong | %RofA | Test Direction |
| 996 | 857+955 | 1439 | 979 | 19.6 | 24.2 | Tangential |
| 1010 | 857+955 | 1453 | 1012 | 18.8 | 24 | |
| 1024 | 857+955 | 1438 | 981 | 20.7 | 26.4 | |
| 996 | 857+982 | 1482 | 1071 | 19.1 | 27.4 | |
| 1010 | 857+982 | 1483 | 1081 | 18.9 | 26.1 | |
| 1024 | 857+982 | 1458 | 1057 | 21.6 | 30.0 | |
| 996 | 857+955 | 1413 | 962 | 21.2 | 27.4 | Radial |
| 1010 | 857+955 | 1425 | 970 | 20.0 | 24.7 | |
| 1024 | 857+955 | 1408 | 947 | 22.0 | 29.0 | |
| 996 | 857+982 | 1445 | 1028 | 20.6 | 27.3 | |
| 1010 | 857+982 | 1441 | 1017 | 20.6 | 28.2 | |
| 1024 | 857+982 | 1450 | 1037 | 22.4 | 34.6 | |

Table II. Effect of Forge and Solution Temperature on Average 704°C Tensile Properties

| Average Elevated Temperature Tensile Properties | | | | | | |
|---|---|---|---|---|---|---|
| Forge Temp. ºC | Solution Temp. ºC | Tensile Stress MPa | Yield Stress MPa | %Elong | %RofA | Test Direction |
| 996 | 857+955 | 1112 | 826 | 18.8 | 20.1 | Tangential |
| 1010 | 857+955 | 1124 | 869 | 19.4 | 23.3 | |
| 1024 | 857+955 | 1107 | 795 | 16.0 | 19.2 | |
| 996 | 857+982 | 1128 | 850 | 14.4 | 17.0 | |
| 1010 | 857+982 | 1166 | 914 | 21.0 | 32.2 | |
| 1024 | 857+982 | 1133 | 865 | 13.8 | 16.9 | |
| 996 | 857+955 | 1104 | 809 | 18.2 | 21.0 | Radial |
| 1010 | 857+955 | 1132 | 859 | 20.2 | 22.6 | |
| 1024 | 857+955 | 1139 | 840 | 16.6 | 19.3 | |
| 996 | 857+982 | 1116 | 826 | 14.0 | 17.8 | |
| 1010 | 857+982 | 1158 | 874 | 14.2 | 17.4 | |
| 1024 | 857+982 | 1121 | 828 | 11.8 | 14.2 | |

No significant influence in the tensile, stress rupture or creep results of the 2 or 8 hour hold at 788ºC of the age cycle was observed.

Average stress rupture life and ductility for the initial phase forgings are given in Table III. There is considerable scatter and the results do not give a clear indication of the effect of either forging or solution temperature on rupture life or ductility.

There were a number of failures in the notch of the stress rupture test bars. Four of the five notch failure specimens were solution treated at 982ºC suggesting that under certain conditions, this solution treatment of alloy 718Plus may be unacceptable.

Average creep life to 0.2% and 0.5% strain is shown in Table III. The results suggest that highest forging temperature gave improved creep life. As was the case for tensile strength, higher solution temperatures appear to promote better creep strength. The effect is more clearly seen for the life at 0.5% strain. It is well documented that larger grain size from high temperature forging will be a significant factor in creep life.

Table III. Effect of Forge & Solution Temperature on Average Stress Rupture & Creep Properties

| Average Stress Rupture(704 ºC 552MPa) & Creep (704 ºC 483Mpa) Properties | | | | | | |
|---|---|---|---|---|---|---|
| Forge Temp ºC | Solution Temp ºC | Stress Rupture | | Creep Life | | Specimen Direction |
| | | Life hrs | %Elong | 0.2% Strain | 0.5% Strain | |
| 996 | 857+955 | 205.3 | 33.0 | 41.9 | 150.0 | Tangential |
| 1010 | 857+955 | 178.5 | 34.8 | 41.6 | 140.6 | |
| 1024 | 857+955 | 206.7 | 37.9 | 43.7 | 156.9 | |
| 996 | 857+982 | 216.5 | 39.5 | 46.8 | 166.3 | |
| 1010 | 857+982 | 84.6* | 41.6* | 46.0 | 164.1 | |
| 1024 | 857+982 | 154.9* | 32.0* | 82.7 | 224.5 | |
| 996 | 857+955 | 217.3 | 32.9 | 60.1 | 191.6 | Radial |
| 1010 | 857+955 | 232.7 | 41.1 | 49.7 | 174.7 | |
| 1024 | 857+955 | 117.6* | 34.6* | 72.3 | 225.0 | |
| 996 | 857+982 | 120.2* | 24.5* | 63.7 | 201.5 | |
| 1010 | 857+982 | 137.1* | 33.6* | 67.0 | 212.8 | |
| 1024 | 857+982 | 314.4 | 38.8 | 122.3 | 285.2 | |

* Notch failure of one specimen in the notch with life of ~1 hour.

The second phase of the study focused on a forge temperature of 1038°C for alloy 718Plus and comparison of properties with waspaloy. Tables IV and V show the tensile properties for both alloy along with the heat treatment parameters. At room temperature alloy 718Plus shows superior tensile and 0.2% proof stress with slightly reduced ductility in comparison to waspaloy. At elevated temperature [704ºC] tensile and 0.2% proof stress, the alloys are comparable with waspaloy again showing greater ductility. Consistent with earlier observations alloy 718Plus solution treatment at 982 ºC gives the highest room and elevated temperature yield strength.

These results indicate that alloy 718Plus has retained the good room temperature capability of alloy 718 while the improved the 704ºC tensile properties suggest alloy 718Plus may be a potential alternative to waspaloy in high temperature applications.

Table IV. Average Room Temperature Tensile Results

| Solution Temp ºC | UTS MPa | 0.2% Proof Stress Mpa | %Elongation | % Reduction of Area | Test Direction |
|---|---|---|---|---|---|
| Allvac® 718Plus™ | | | | | |
| 857+982 | 1419 | 1072 | 22.2 | 32.4 | Radial |
| 857+968 | 1424 | 1018 | 22.5 | 28.8 | |
| 857+955 | 1436 | 1046 | 21.5 | 27.0 | |
| 955 | 1424 | 983 | 22.2 | 25.3 | |
| Waspaloy | | | | | |
| Subsolvus | 1348 | 940 | 27.2 | 35.7 | Radial |

Table V. Average 704ºC Tensile Test Results

| Solution Temp ºC | UTS MPa | 0.2% Proof Stress MPa | %Elongation | % Reduction of Area | Test Direction |
|---|---|---|---|---|---|
| Allvac® 718Plus™ | | | | | |
| 857+982 | 1169 | 879 | 18.9 | 21.3 | Radial |
| 857+968 | 1151 | 820 | 21.8 | 25.6 | |
| 857+955 | 1151 | 812 | 25.5 | 26.3 | |
| 955 | 1151 | 812 | 26.4 | 28.6 | |
| Waspaloy | | | | | |
| Subsolvus | 1128 | 837 | 33.8 | 52.6 | Radial |

The average results of second phase stress rupture testing at 704ºC and 552Mpa for alloy 718Plus and waspaloy are given in Table VI. At the time of writing, testing is not complete but the results indicate that alloy 718Plus solution treated at 982ºC shows comparable stress rupture life when solution treated at 982ºC with waspaloy. One of the six alloy 718Plus stress rupture tests for 982ºC solution treated specimens failed prematurely at the notch. Metallographic evaluation of the alloy 781Plus test specimens indicates delta phase grain boundary precipitation has an influence on stress rupture notch sensitivity. Notch ductility issues and the influence of precipitation on mechanical properties and fracture in alloy 718 and alloy 706 are well documented [15, 16, 17, and 19].

Table VI. Average Stress Rupture (704 ºC 552MPa) & Creep (704 ºC 483MPa) Test Results

| Solution Temp. ºC | Stress Rupture | | Creep Life | | |
|---|---|---|---|---|---|
| | Life hrs | % Elong. | 0.25% Strain hrs | 0.5% Strain hrs | Test Direction |
| Allvac® 718Plus™ | | | | | |
| 857-982 | 407 | 27.6 | - | - | Radial |
| 857-982 | 502* | 28.1 | 247 | 392 | Tangential |
| 857-968 | TBD | TBD | TBD | TBD | |
| 857-955 | 252 | 28.7 | 333 | 445 | |
| 955 | 288 | 28.3 | TBD | TBD | |
| Waspaloy | | | | | |
| Subsolvus | 434 | 21.1 | 66 | 162 | Tangential |

* Average life for two specimens, third specimen failed prematurely with a Notch failure.

The microstructure of alloy 718Plus stress rupture specimens in notch ductile (500 hr life) and notch brittle conditions are shown in figures 5 and 6 respectively. Both samples were forged at 1038ºC and solution treated at 982ºC. The microstructure from the two specimens is similar, but the delta phase precipitation appears to be greater on the grain boundaries of the notch ductile specimen than the notch brittle specimen. This observation is based on a visual comparison as it has not been possible to quantify the delta phase concentration at the grain boundaries.

The microstructure from alloy 718Plus solution treated at 955ºC and 968ºC are shown in Figures 7 and 8, respectively. Comparison of the Figures 7 and 8 with Figures 5 and 6 show a higher concentration of grain boundary delta phase precipitation on the lower temperature solution treated material.

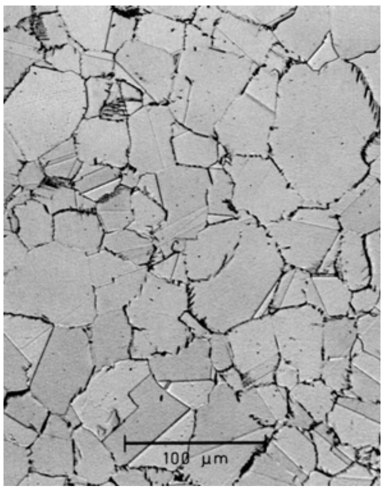


Figure 5. 500 hr Stress Rupture Life

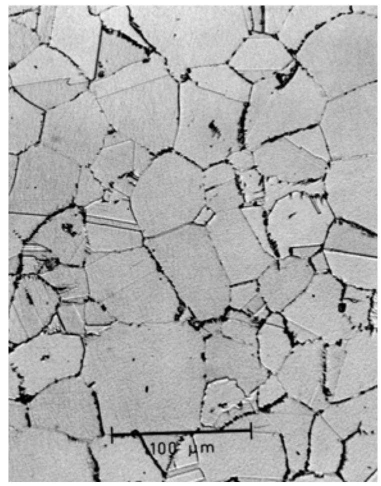


Figure 6. Stress Rupture Notch Failure

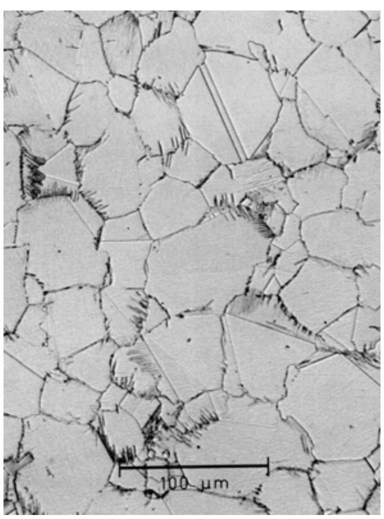


Figure 7. Alloy 718Plus™ 955 ºC Solution

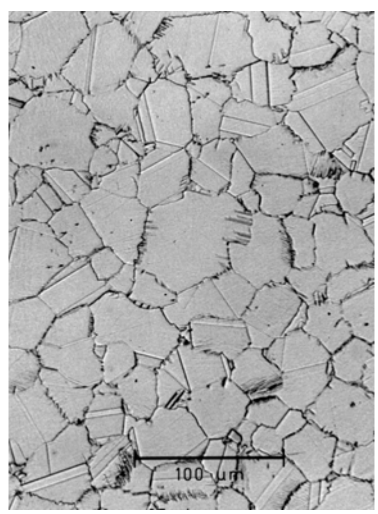


Figure 8. Alloy 718Plus™ 968 ºC Solution

Table VI also shows the average available creep life to 0.25% and 0.5% strain for the second phase alloy 718Plus forgings solution treated at 982ºC and 955ºC and for waspaloy. Alloy 718Plus in both solution treated conditions shows improved creep life over waspaloy. It is not possible to draw a conclusion in comparing the phase one and two alloy 718Plus forging creep lives. Further investigation of the effects of forging and heat treatment on creep life is required to clarify these results.

## Summary and Conclusions

The structure and mechanical properties of alloy 718Plus and waspaloy forgings were evaluated. The following conclusions can be drawn from this study:

- Pancake forgings made of alloy 718Plus displayed tensile, stress rupture, and creep properties comparable to supersolvus processed waspaloy.
- The best tensile properties were obtained for the lower forge temperatures and higher solution temperatures whereas the best creep resistance is obtained at higher forge and solution temperatures used in this study.
- Grain size and delta phase precipitation exerts a strong influence over stress rupture properties, strength and ductility.
- Alloy 718Plus exhibited stress rupture notch brittle behavior that appears to be related to grain boundary delta precipitation.
- The results obtained to date suggest that, through further optimization of thermomechanical processing parameters and heat treatment, alloy 718Plus can consistently achieve mechanical properties approaching those of waspaloy.

## References

1. J.K. Tien, et al., *Proceedings of the 1990 High Temperature Materials for Power Engineering Conference*, ed. E.B. Bachelet, et al. (Kluwer Academic Publisher, 1990), 1341-1356.

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

3. J.P. Collier, S.H. Wong, J.C. Phillips and J.K. Tien, *Metallurgical Transactions A*, 1988, Vol. 19A, 1657-1666.

4. J.A. Manriquez, P.A. Bretz, L. Rabenberg and J.K. Tien, *Superalloys 1992*, edited by S.D. Antolovich, et al., TMS, 1992, 507-516.

5. R. Cozar and A. Pineau, *Metallurgical Transactions A*, Vol. 4, 1973, 47-59.

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

7. E. Andrieu, N. Wang, R. Molins and A. Pineau, *Superalloys 718, 625, 706 and Various Derivatives*, edited by E.A. Loria, TMS, 1994, 695-710.

8. E. Gou, F. Xu and E.A. Loria, *Superalloy 718 – Metallurgy and Applications*, edited by E.A. Loria, TMS, 1989, 567-576.

9. E. Gou, F. Xu and E.A. Loria, *Superalloys 718, 625 & Various Derivatives*, edited by E.A. Loria, TMS, 1991, 389-396.

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

11. R.A. Schafrik et al., *Superalloys 718, 625, 706 and Various Derivatives*, edited by E.A. Loria, TMS, 2001, 1-11.

12. W.D. Cao and R.L. Kennedy, *Superalloys 718, 625, 706 and Various Derivatives*, edited by E.A. Loria, TMS, 2001, 477-488.

13. W.D. Cao and R.L. Kennedy, *Superalloys 718, 625, 706 and Various Derivatives*, edited by E.A. Loria, TMS, 1994, 463-477.

14. W.D. Cao and R.L. Kennedy, *Superalloys 718, 625, 706 and Various Derivatives*, edited by E.A. Loria, TMS, 1997, 511-520.

15. R. Molins, E. Andrieu and A. Pineau, *Superalloys 718, 625 and Various Derivatives*, edited by E.A. Loria, TMS, 1991, 589-602.

16. G. Sjoberg and N.-G. Ingesten, *Superalloys 718, 625 and Various Derivatives*, edited by E.A. Loria, TMS, 1991, 603-620.

17. H. Feldstein and O. Mendoza, *Superalloy 718, Metallurgy and Applications,* edited by E.A. Loria, TMS, 1989, 655-671.

18. Y. Desvallées, M.Bouzidi, F. Bois and N. Beaude, *Superalloys 718, 625 and Various Derivatives,* edited by E.A. Loria, TMS, 1991, 281-291.

19. W. Chen and M.C. Chaturvedi, *Superalloys 718, 625 and Various Derivatives*, edited by E.A. Loria, TMS, 1991, 567-577.